

Student Reasoning Strategies Concerning Periodic Trends

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Dedication

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Abstract

The periodic table is recognized as one of the most powerful tools in science. While it is included in virtually all high school and undergraduate general chemistry curricula, it remains a mystery to many chemistry students who find it impossible to decode. Students are often able to predict periodic trends concerning atomic radius, ionization energy, and electronegativity, however they experience significant difficulty when trying to explain why these trends occur. One way to explore the cause of these difficulties is to focus on the reasoning strategies used by students as they attempt to explain periodic trends.

This study investigated student reasoning strategies used to explain periodic trends in atomic and ionic radius, ionization energy, electronegativity, and reactivity. A theoretical framework of scientific reasoning, as it applied to qualitative problem solving, was utilized to identify how the problem solving constraints of domain specific knowledge (DSK) and heuristics were utilized by students as they attempted to explain the periodic trends. This phenomenographic study used semi-structured interviews to assess student reasoning strategies, as well as selected exam and assignment questions to determine the DSK for each student.

The findings suggested that student understanding in the domain of electrostatic forces had the greatest influence on the type of reasoning strategies used. Those students with adequate understanding of electrostatic forces had more resources with which to construct explanations that integrated several scientifically appropriate force related factors. Those students without adequate understanding concerning electrostatic forces

tended to limit themselves to the use of one factor that was not always adequately justified. They also tended to exhibit fixation by focusing on the same factor for multiple situations, even when that factor was no longer the most appropriate. When presented with an unfamiliar problem there was an increase in the number of one-factor strategies used, with a corresponding decrease in the number of force related explanations. This study suggested that an analysis of student explanations about difficult chemical topics might be helpful in diagnosing the underlying causes of student learning difficulties, and it also highlighted the need to help students learn how to formulate appropriate scientific explanations.

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CHAPTER 1: INTRODUCTION

The periodic table has long inspired both wonder and fear in chemistry students, and for good reason. Wonder because it is a natural system of classification that gives an almost limitless expanse of information to both the novice and expert chemist. Fear, because the table challenges students to think critically in new and unfamiliar ways. Martin Kemp (1998) described it as “The king of all tables, ruling over the reconfiguring of the science of chemistry and governing much of its subsequent conduct” (p. 527). Hill and Lederman (2001) describe the periodic table as the “starting point for chemistry” (p. 33). The arrangement of the table highlights a characteristic of elements called periodicity, which is often described as “The periodic law”. An early summary of this law was given by Mendeleev (Kemp, 1998) when he wrote, “The elements, if arranged according to their atomic weights, exhibit an evident periodicity of properties” (p. 634). Modern scientists arrange the elements by atomic number rather than atomic weights, but the periodic table remains a vital tool for anyone interested in chemistry.

Rationale

Virtually all chemistry curricula include periodicity with the aim that students will learn not only to recognize patterns in the periodic table, but also to explain and predict certain key properties of the elements by observing their placement in the table. Volkmann (1996) said, “The periodic table is one of the most fundamental organizing systems of chemistry. However, for most high school students, the periodic table may as well be written in hieroglyphics” (p. 37). Volkmann was referring to students’ ability to see these patterns and comprehend their significance. A study of Spanish baccalaureate

students (Franco-Mariscal, Oliva-Martínez, & Gil, 2015) found that 66% of the participants were able to appropriately explain the classification of elements using the periodic table, 37.9% could explain the existence of trends in properties using electronic configurations based on the periodic table, but only 7.5% could correctly explain the trend in atomic size. Similarly, in a study of 240 second semester General Chemistry students in a New York Community College, 80% did not understand the trends in atomic radius (Salame, Sarowar, Begum, & Krauss, 2011). This indicates that some students have difficulty understanding the reasons for periodic trends even when they can see that these trends exist. For this reason, a more in-depth exploration that investigates the type of reasoning strategies that students use when attempting to explain periodic patterns in the ‘king of all tables’ is warranted.

After learning to recognize that patterns are present within the structure of the periodic table, the student is further challenged to predict and explain these patterns using their knowledge of atomic structure and electrostatic forces. One of the most basic trends that a student might be expected to explain is the trend in atomic size, which is traditionally expressed in terms of the radius of the atom. This trend is easily visualized, exhibiting only a few exceptions within the representative elements. The trends in atomic radii are directly related to the more abstract concepts of ionization energy (Eymur, Çetin, & Geban, 2013), electronegativity (Jensen, 2003; Leach, 2013), chemical bonding (Eymur et al., 2013; Nicoll, 2001; Wang & Barrow, 2013), and polarity (Wang & Barrow, 2013). Wang and Barrow (2013) state that an understanding of the above topics

is necessary if the student is to progress to more advanced ideas in both organic and inorganic chemistry.

While there is certainly no lack of research about the periodic table and the difficulties that students encounter, there have been significantly fewer studies that focus on student reasoning strategies for explaining periodic trends and how this reasoning might be shaped by the student's specific knowledge of atomic structure (the particles that make up an atom and their relative placement within the atom), electrostatic forces within the atom, and the ionization process. There have been studies concerning atomic size (Eymur et al., 2013; Salame et al., 2011), as well as ionization energy (Taber, 1998; Tan et al., 2008; Tan & Taber, 2009, 2009), which focus primarily on student misconceptions and how they affect the predictions that are given for periodic trends in either atomic size or ionization energy. The study that most closely approximates the goals of the present study focused on how the conceptual framework of high and low content knowledge students affected their ability to explain atomic radius, electronegativity, bonding, and polarity (Wang & Barrow, 2013). In contrast to previous research, an investigation which focuses primarily on the reasoning process, rather than specific explanations used by students as they predict periodic trends might help us to better understand some of the difficulties that students experience.

Purpose and Potential Significance of Study

The purpose of this study was to investigate the reasoning strategies used by students as they attempted to explain periodic trends and to see how their understanding

of atomic structure, the electrostatic forces within the atom, and the ionization process shaped the chemical explanations that they produced.

Given the pivotal nature of the periodic table to the discipline of chemistry, a more complete understanding of the difficulties experienced by students as they strive to unlock the secrets of this organizational tool and apply it to chemical problems is worthwhile. With this knowledge, instructors might be enabled to design learning experiences that would allow students to develop ways of thinking that are more effective as they learn to use the periodic trends to predict chemical properties. Instructors might also see the importance of helping students to develop metacognitive awareness of the reasoning strategies they are using so that they can more accurately assess the limitations of less sophisticated strategies, and identify those situations in which more complex strategies are needed.

Framework and Research Questions

Framework. The present study is structured around the broad framework of scientific reasoning as it applies to qualitative problems in chemistry. Scientific reasoning is an important goal in science education (National Research Council, 1996). Dunbar and Klahr (2012) suggest that a central component of much scientific reasoning involves the development of causal explanations between variables of interest (such as atomic structure and atomic radius). This often involves the search for a causal mechanism which explains the way in which one variable acts to cause the other. This type of “causal/mechanical” explanation views events as being caused by the properties and interactions of the participants involved (Talanquer, 2010).

Scientific thinking, or reasoning has also been closely associated with problem solving (Dunbar, 1998; Klahr, 2002; Morris, Croker, Masnick, & Zimmerman, 2012; Simon, 1992). According to Dunbar (1998), a problem is defined as a task which does not have an obvious solution. Fundamental to problem solving is the process of sifting through the set of operations (actions) and possible solutions that are available to the problem solver in order to arrive at the goal that has been set (Dunbar, 1998; Klahr, 2002; Newell & Simon, 1972). The set of possible solutions can be quite large even for fairly simple problems (Newell & Simon, 1972). Making the task even more difficult is the absence of a prescribed formula or method that guarantees a solution (Dunbar, 2000). The time and cognitive effort needed to search through every possible solution can become prohibitive, making it necessary to find ways to constrain, or narrow the search through the use of suitable strategies (Dunbar, 1998; Kaplan & Simon, 1990; Klahr, 2002).

The proposed study focuses on two types of constraint. The first is domain specific knowledge which is critical in the search for solutions (Kaplan & Simon, 1990). Specific knowledge in the problem domain enables the solver to focus on ideas that are critical to a solution while ignoring irrelevant details. The knowledge required is not simply a collection of facts, but a web of interrelated concepts that displays patterns and structure (Larkin, McDermott, Simon, & Simon, 1980; Lopez, Shavelson, Nandagopal, Szu, & Penn, 2014). By seeing how the known facts are related to each other, it may be possible to see their relationship to the problem at hand (Polanyi, 1974). This background

knowledge can then be used to support student reasoning in the problem's solution (Talanquer, 2009; Wang & Barrow, 2013).

The second problem solving constraint that will be explored is the student's use of reasoning strategies including heuristics. A heuristic may be defined as a rule of thumb that is useful in guiding the problem solver to the problem solution by reducing computational load (Dunbar, 1998; Simon, 1990, 1992). While heuristics are indispensable for use with complex problems, unlike algorithms, they do not guarantee the correct solution. Algorithms are typically procedures that when used appropriately, always produce a correct result (Dunbar, 1998; Graulich, Hopf, & Schreiner, 2010). The power of heuristics does not lie in their ability to find "truth" but as a means of giving direction when information is limited (Graulich et al., 2010) and as such are neither blind, nor totally rational (Aliseda, 2004). Polanyi (1974) describes problem solving as a heuristic act which enables one to "leap across a logical gap" (p. 125) in a way that utilizes vague maxims rather than specific rules. Dependency on heuristic strategies seems to change proportionally with the complexity of the task and the variety of cues that must be considered and weighed for an optimal judgement (Maeyer & Talanquer, 2010; Shah & Oppenheimer, 2008; Taber, 2009). Shah and Oppenheimer (2008) propose that since the primary purpose of heuristics is to reduce the effort needed for a particular task, heuristics should be classified according to the way in which effort reduction is accomplished. They use the weighted additive rule as the ideal standard for optimal judgements. It requires the completion of five tasks: the complete identification of cues, recalling the value (often numerical) for each cue, assessing the weight (importance) of

the cue, integrating the information gathered, and choosing the solution that promises the highest value. They then suggest that heuristics be classified by the way in which they reduce cognitive demands by either eliminating or simplifying the execution of these five tasks.

Graulich, Hopf, and Schreiner (2010) contend that heuristics are an important tool used by professional chemists in order to structure the vast amount of chemical information that is needed to solve problems that they regularly encounter. The use of heuristics enables chemists to focus on essential information without becoming mired in the details. Unfortunately, heuristics as used by novices may sometimes introduce problems. A short-cut strategy might lead the student to a correct answer the majority of the time without the related content knowledge needed to make the answer meaningful. The lack of the requisite chemical knowledge may lead to difficulties with future knowledge construction (Graulich, 2015). When heuristics are used as a crutch to make up for a lack of knowledge, students may struggle to identify appropriate cues, misuse the cues they do identify, and overuse the heuristic in general (McClary & Talanquer, 2011).

In the present study, students were asked to predict and/or explain several periodic trends. The reasoning strategies that they used to explain the various trends were categorized and compared in order to learn what type of reasoning was most prevalent, and to identify conditions that seemed to favor the use of heuristics rather than the more effortful type of causal/mechanical reasoning that recognizes the interaction of multiple factors, and weighs them appropriately. Once student reasoning is more

thoroughly investigated and understood, it might be possible to gain some insight into how these reasoning strategies might be developed into more effective ones.

In the past, much of the research in chemical problem solving has focused on problems that involve mathematical reasoning (Bodner & Herron, 2006; Gabel & Bunce, 1994). Less research has been done on the ways that students reason with respect to qualitative problems (Christian & Talanquer, 2012). When qualitative problem solving has been addressed, the tendency has been to focus on misconceptions or alternative conceptions. These two terms will be used interchangeably in this study to mean the ideas students have regarding scientific concepts after being exposed to formal models or theories, that would not be deemed as scientifically acceptable (Boo, 1998). Over time a vast number of misconceptions have been inventoried by topic, which while helpful, can become overwhelming for any instructor attempting to address them all (Duit, 2009; Garnett, Garnett, & Hackling, 1995; Kind, 2004; Nakhleh, 1992; Talanquer, 2006). Due to the number and variety of misconceptions that are possible, Talanquer (2006) suggests that a more productive approach would be to look for the source of the problems, or patterns of reasoning that students exhibit. The use of heuristics as a major constraint in the problem solving of qualitative problems offers a powerful means to explore the differences in student reasoning.

In the present study, the scientific reasoning/problem solving framework was useful to identify how the problem solving constraints of domain specific knowledge and reasoning strategies are utilized by students as they attempt to create explanations for periodic trends. The domain specific knowledge to be considered encompasses the areas

of atomic structure, electrostatic forces operating within the atom, and the ionization process. Student reasoning strategies involving both heuristic and causal/mechanical explanations that weigh multiple factors will be investigated.

Research questions. The goal of this study is to examine the reasoning strategies used by undergraduate chemistry students to explain the periodic trends of atomic and ionic radii, ionization energy, electronegativity, and reactivity in light of the two constraints of domain specific knowledge and reasoning strategies. The research questions that will guide the study are as follows:

- 1. What are the types of reasoning strategies used by undergraduate general chemistry students in their explanations of periodic trends including atomic radii, ionic radii, ionization energy, electronegativity and reactivity?*
- 2. How does domain specific knowledge concerning atomic structure, electrostatic forces operating within the atom, and the ionization process shape the reasoning strategies of undergraduate general chemistry students in regard to the above trends?*
- 3. What effect will an unfamiliar periodic trend problem have on the reasoning strategies utilized by undergraduate general chemistry students?*

Chapter Summary

This chapter presented the rationale, purpose, theoretical framework and research questions that will form the basis for the present study. The pivotal position of the periodic table to the study of chemistry has been illustrated, as well as the difficulty that students encounter when trying to explain the trends contained within it. This study

investigates student understanding of periodic trends through the lens of scientific reasoning and problem solving using the constraints of domain specific knowledge and reasoning strategies which include heuristics. In the next chapter, an overview of the research literature concerning the domain specific knowledge required in the areas of atomic structure and forces, the heuristics commonly used by chemistry students, and student conceptions regarding the periodic trends is presented.

CHAPTER 2: LITERATURE REVIEW

This chapter reviews the literature concerning student reasoning as it pertains to the problem solving processes in chemistry, specifically in the area of periodic trends. Due to the inherent complexity of any problem solving task, constraints are needed in order to narrow the search for solutions. This review elaborates on two constraints that are especially applicable to problem solving: domain specific knowledge (DSK) and reasoning strategies (including heuristics), and apply them more specifically to the area of periodic trends. In addition to reviewing the literature about the two areas constraining student reasoning, this chapter also reviews research that specifically targets student explanations and understanding of periodic trends.

In the present study, students were given a series of problems that required them to predict and explain several periodic trends. The type of reasoning required for a scientifically appropriate explanation has been described as causal/mechanical reasoning, in which the prediction is explained by a set of interactions between particles that lead to the formation of the pattern being predicted. Students needed to choose from among the various concepts that were a part of their DSK those that would be most helpful in solving the problem, and then explain how the concepts (particles and forces) would interact to produce the predicted result. In this study, the term “factor” will denote the specific concepts that students utilize to build their explanations. At times, a factor might include both a particle and a force, such as electron repulsion, whereas at other times it might be simply a structural feature of the atom such as energy level or mass.

Domain Specific Knowledge

The domain specific knowledge (DSK) referred to in the context of this study is knowledge which must have been previously learned in order for the problem solver to predict and explain periodic trends in a scientifically appropriate manner. Larkin (1980) asserts that problem solvers in every discipline require a significant amount of domain knowledge in order to become skillful. This knowledge is instrumental in guiding the problem solver to relevant information or factors that will assist in solving the problem (Morris et al., 2012). When a student has gaps in his/her knowledge of a topic, it leads to confusion and faulty reasoning (Nakiboglu, 2003; Taber, 2003b; Wang & Barrow, 2013). Talanquer (2015) expands on this idea with his use of “threshold concepts”. A threshold concept is one that opens the door to entirely new ways of thinking in the discipline. As such, it transforms a student’s thinking and allows them to integrate previously learned strands of knowledge. One characteristic of a threshold concept is that it is troublesome, often conceptually difficult or perhaps even alien in the sense of being counter-intuitive, functioning as a barrier to further progress in a subject (Park & Light, 2009). Two concepts will be explored as potential threshold concepts that open the door to understanding periodic trends as well as other fundamental ideas important to chemistry: atomic structure and electrostatic forces within the atom. Both atomic structure and forces have been identified as core ideas that make up the physical science standards (NGSS Lead States, 2013) for K-12 science education in the United States. Gillespie (1997), who worked on undergraduate chemistry curriculum reform on an American Chemical Society sponsored Task Force, included atomic structure and electrostatic

forces in his discussion of the ‘great ideas’ of chemistry. A third concept, the ionization process that occurs when a metal atom becomes a positive cation will also be briefly explored. An understanding of the ionization process is necessary to explain ionization energy trends, but would probably not be considered a threshold concept.

Atomic structure. Atomic structure has been identified as a threshold concept in chemistry (Park & Light, 2009; Talanquer, 2015). Talanquer (2015) asserts that atomicity is a threshold concept necessary for “making sense, predicting, and controlling the properties of matter” (p. 4). A student attempting to explain periodic trends is attempting to make sense of, and predict the properties of atoms. Without a clear understanding of atomic structure, this will not be possible. Tabor (2003a) describes the topic of atomic structure as troublesome because learning about atomic structure is difficult, and many students continue to have problems with related topics that are more advanced. While the structure of an atom determines and includes the electrostatic forces within it, forces will be considered separately in this study. The atomic structure domain will include the identity of sub-atomic particles, along with their number, charge, and placement within the atom, while the electrostatic forces domain encompasses how the particles interact with each other. This differentiation has been chosen due to the distinct nature of the problems that students experience in each area, which will be elaborated upon in the following paragraphs.

While atomic structure is emphasized in virtually all chemistry curricula, students continue to experience problems both in understanding and applying the concepts involved. Some students are unable to discern the difference between protons, neutrons,

electrons, and ions (Cokelez & Dumon, 2005). Often the terms ‘orbital’, ‘shell’, ‘orbits’, and ‘energy levels’ are used interchangeably (Nakiboglu, 2003; Nicoll, 2001) or the concept of energy level is missing entirely (Wang & Barrow, 2013). Students also have trouble distinguishing between atomic models and reality (Boo, 1998; Talanquer, 2015). An illustration of this confusion in the area of atomic structure is the misconception that orbitals are boxes that can be filled by electrons (Nakiboglu, 2003) a conception that probably originates in the orbital diagrams that are used to model how electrons are distributed among available orbitals. Students with lower conceptual understanding in the area of atomic structure often failed to grasp the meaning and limitations of the atomic models that they used, which then hindered their ability to visualize the atoms or use the models appropriately (Wang & Barrow, 2013).

During the course of their education, students are taught about atomic structure by being exposed to atomic models with graduated levels of sophistication. This raises the question as to which model is necessary for students to master in order to explain periodic properties. The atomic model used most consistently by undergraduate students is the Bohr atom, with only a few progressing to the quantum model despite the prominent place that the quantum model has in the curriculum (Park & Light, 2009; Wang & Barrow, 2013). Taber (2003b) asserts that while a clear understanding of energy levels is absolutely necessary in order to understand periodic trends, the Bohr atom is sufficient to enable the student to explain basic trends in ionization energy. Since the trends in ionization energy are dependent on the trends in atomic radii, it can be inferred that the student must have attained an understanding of the Bohr model of the atom in

order to explain both of these trends. When the student attempts to explain disruptions in the ionization energy trends however, Taber (2003b) asserts that the quantum model of the atom is needed as the disruptions can only be explained by referring to the electron arrangement in individual orbitals. Wheeldon (2012) suggests that students who were able to use the quantum model in explaining ionization energy were more likely to discuss the effects of electron-electron interactions in terms of repulsion rather than nuclear shielding, and showed more scientific depth in their causal arguments. It would appear, based on these studies, that while a good understanding of the Bohr model is sufficient to explain most periodic trends, an understanding of the quantum atom is helpful to explain exceptions to these trends and enable students to provide a more nuanced explanation of the forces involved.

Electrostatic forces within the atom. The second category of domain specific knowledge that students must understand if they are to explain periodic trends is that of electrostatic forces within the atom (Becker & Cooper, 2014; Taber, 2003b). Gillespie (1997) states, “Electrostatic forces are the only important force in chemistry” (p. 862). If students do not connect their understanding of atomic structure to electrostatic forces it is not possible to give a scientifically appropriate explanation for any periodic trend involving energy or reactivity (Becker & Cooper, 2014). Electrostatic forces within the atom include both attractive and repulsive forces and are mediated by Coulomb’s law (which states that force is directly proportional to charge and inversely proportional to the square of the distance). In a study comparing the conceptual framework of chemistry students with low content knowledge to those with high content knowledge (Wang &

Barrow, 2013), it was found that the conceptual frameworks of students with low content knowledge were missing the principles of electrostatic forces, particularly the influence of nuclear charge on the electrons. In explaining chemical phenomena, these students often followed general rules that were never justified or used anthropomorphic explanations instead of scientific principles.

While very few studies focus on students' conceptions of electrostatic forces within the atom, studies on bonding, intermolecular forces, molecular polarity, and potential energy capture some of the misconceptions that students exhibit concerning electrostatic forces in general. As already mentioned, many students simply ignore the influence of electrostatic forces when explaining periodic trends (Eymur et al., 2013; Salame et al., 2011; Wang & Barrow, 2013). In other cases, students discuss the influence of "forces" in a general manner as an explanation for chemical phenomena when they cannot think of any more specific explanation (Nicoll, 2001) or have a vague notion that the forces of attraction and repulsion generated from the nucleus balance each other (Wang, 2007). Studies have shown that some students are aware of specific electrostatic forces within the atom, but have misconceptions about the nature of the interactions. These misconceptions included the concepts that the nucleus is not attracted to electrons (Wang, 2007), or that electrons attract each other (Nicoll, 2001). Another type of misconception that students sometimes exhibit concerns the amount of attraction that electrons feel. These students reason that there is a set amount of nuclear attraction that is shared equally by the valence electrons, so that if an electron is added, there will be less attractive force for each individual electron (Taber, 1998, 2003b; Wang, 2007).

This last misconception has been named the “conservation of force” misconception and has been found to be particularly difficult to dislodge as it often leads to correct predictions of periodic trends (Taber, 1998).

The ionization process. The third category of domain specific knowledge that students must understand if they are to explain periodic trends is the ionization process that occurs when a neutral atom loses an electron. Of the fourteen periodic trends included in this study, eight directly involved the ionization process. Trends in ionization energy cannot be explained if the ionization process itself is not understood. While the specific process of ionization is not mentioned as a core idea in the physical science standards (NGSS Lead States, 2013) for K-12 science education, it is one of the chemical processes addressed in the 9-12 standard PS1.B dealing with chemical processes and the ensuing energy changes. The literature in the area of ionization is limited to studies regarding student misconceptions concerning ionization energy. The primary misconceptions that students demonstrated dealt with problems using the octet rule, and misconceptions about forces (Taber, 1998, 1999, 2003b; Taber & Tan, 2011; Tan et al., 2008; Tan & Taber, 2009; Tan, Taber, Goh, & Chia, 2005). These topics will be covered in the section on student understanding and explanations of periodic trends.

Reasoning Strategies Utilized by Students to Explain Chemical Ideas

Even if a student has demonstrated mastery of domain specific knowledge pertinent to the problem context, they must still be able to identify relevant factors that are applicable to the specific situation, apply concepts in an appropriate manner, and find a way to weight the various concepts given the unique context of the problem and then

integrate the effect of all concepts in arriving at a solution. The process of explaining a periodic trend requires a fairly sophisticated level of reasoning. Using the weighted additive rule as outlined by Shah and Oppenheimer (2008) as an optimal approach to problem solving, an ideal explanation concerning a periodic trend in a group or period would identify all factors along with the effect they would have on the trend in question. Factors to be considered include any change in the principle quantum number in which valence electrons reside (which helps to determine the relative size of the orbitals within the shell), the effective nuclear charge (which is generally simplified to be the number of protons, which attract valence electrons, minus the number of core electrons, which repel valence electrons), any additional repulsion caused by valence electrons, and the valence electron arrangement within the individual orbitals (since paired electrons repel each other). While there may be other factors, these are the ones that a general chemistry student might be expected to consider. The student would need to decide on the value of the factor (the number of protons, core electrons etc.), weigh the relative importance of each factor, and finally integrate the effect of all factors in order to choose a suitable solution. Because of the inherent complexity of this and other problem solving tasks in chemistry, students will often rely on particular reasoning strategies (heuristics) that simplify the process. These strategies are most probably influenced by the student's limitations in cognitive processing ability and the environment in which the task is to be completed (Shah & Oppenheimer, 2008). Problems may arise because these simplified strategies (heuristics) are often used by novice problem solvers in ways that may not guarantee optimal results (Taber, 2009).

Much research has been done describing specific heuristics, with each group of researchers defining their own unique terms for particular heuristics that are often very similar in nature. This leads to a significant amount of redundancy resulting in confusion (Shah & Oppenheimer, 2008). In addition to the research that was not specific to any one domain or discipline, there has also been significant research identifying heuristics used by chemistry students, many of which are very similar to the heuristics used more generally. This study starts with those heuristics described by researchers in the chemistry discipline, and then adds heuristics that have more universal utility as needed.

Heuristics used in chemistry. After an analysis of the literature pertaining to alternative conceptions as expressed by chemistry students, Talanquer (2006) reorganized his findings according to the patterns of reasoning used. His analysis of these patterns led him to describe several broad categories of heuristics frequently used by chemistry students, which included association, reduction, and fixation as shown in Table 2.1.

Table 2.1

Heuristic Categories Used by Chemistry Students

Category	Heuristic	Description and Example
Association	Availability	The most readily available or familiar factor is used to explain a phenomena: Sodium is described as more reactive than rubidium because the student is familiar with sodium.
	Similarity	The causal factor shares similar features with the result: A Ca^{2+} ion is described as having a larger radius than a K^{+} ion because it has a larger charge.
	Representativeness	Using explicit similarities to judge whether a system belongs to a certain class: A metal is reactive because it is ionized, and the rules for ionization apply.
	Additivity	The properties of a system are evenly distributed among the individual components: When there are more protons than electrons, each electron experiences a greater share of the total force.
Reduction	One-reason	The properties of a system are seen as being caused by a single factor. Other competing factors not considered: The atomic radius of potassium is larger than the radius of sodium because potassium has more energy levels.
	Lexicographic	Factors are considered in sequential order until one differentiates among the alternatives: Fluorine and lithium both have their valence electrons in the second shell, but fluorine has more electrons which causes more repulsion.
	Satisficing	The student will often start by considering the most recently used or favorite factor and if it seems to offer an explanation, then no further factors are explored.
Fixation	Fixation	Repeatedly use the same strategy even when the problem changes: A student only considers the number of shells to predict every periodic trend.
Empirical Assumption	Teleological	The consequence of an event is given as the cause through the lens of intentionality or purpose: The atom wants to have a full shell of electrons.
	Essentialism	Substances have an essential character that is the invisible cause for change: There is something about sodium's nature that makes it very reactive.

Association. The association type heuristics describe the arbitrary application of rules to connect cause and effect. He went on to describe several association heuristics including the availability, similarity and additivity heuristics. The availability heuristic is demonstrated when causes are chosen based on their familiarity or cognitive accessibility to the student (Talanquer, 2006). An example would be if a student predicted that sodium is more reactive than rubidium simply because they recognize sodium as a familiar element that is referred to more frequently in class than rubidium.

Recognition and familiarity are other terms for heuristics that have been employed when the problem-solver decides on a solution based upon having had prior experience with a specific solution option (Maeyer & Talanquer, 2010; Todd & Gigerenzer, 2000). Recognition type heuristics are sometimes classified as ‘ignorance-based’ heuristics (Todd & Gigerenzer, 2000) because the only information available to the decision-maker is whether or not they have ever seen an option before.

While the availability heuristic associates a familiar, or readily available factor as the cause for an effect, similarity, uses the association of a common characteristic (Talanquer, 2006). Using this heuristic, a student might associate a large ionic charge with a large ionic radius and give no further justification.

A more sophisticated (and useful) form of similarity is when two problems display explicit similarities that allow them to be classified as belonging to the same category of problem. This heuristic is called representativeness (Maeyer & Talanquer, 2013; Shah & Oppenheimer, 2008). If the student is familiar with the behavior of acids,

and recognizes an unfamiliar substance as being an acid, then predictions can more easily be made about its behavior.

Additivity, also an association heuristic, occurs when effects are equally distributed among equivalent system portions (Talanquer, 2006). In the context of periodic trends, the additivity heuristic is sometimes used to express the idea that the nuclear force of attraction is equally divided among electrons, therefore if the number of electrons is reduced while the number of protons remains constant, each electron will feel more nuclear force.

Reduction. Talanquer's (2006) second heuristic category is reduction. This strategy is employed when the problem solver reduces the factors to be considered. Students using reduction style heuristics isolate particular features of the problem and do not see the problem as a whole (McClary & Talanquer, 2011). Within this category is the one-reason decision making heuristic in which a property in a system is seen as being caused by only one variable or factor. Tan et al. (2008) used the term relation-based thinking to describe any one-reason strategy. Relation-based thinking occurs when a problem-solver does not appreciate how a change in one factor might be cancelled by a change in another, such as increased nuclear charge being cancelled out by increased electron repulsion. Furió, Calatayud, Bárcenas, and Padilla (2000) had a similar idea in mind when they used the term functional reductionism. A problem solver engages in functional reductionism when they reduce the complexity of a problem by reducing the number of factors, or by equating two concepts that are very similar. An example might

be when a student describes a molecule as being polar because one of the bonds is polar, instead of looking at both bond polarity and the molecular shape.

In some cases, the problem solver is aware of multiple factors, but in order to simplify the problem, a decision is made as soon as one factor differentiates between the options making it a sequential process of considering one factor at a time (Todd & Gigerenzer, 2000). This decision making behavior has been described using the term lexicographic (Fishburn, 1974; McClary & Talanquer, 2011; Todd & Gigerenzer, 2000). When using the lexicographic heuristic, the problem solver looks at factors one by one, comparing their values, (such as the number of electrons, or the number of protons) and stops as soon as there is a significant difference in the value of the factor being considered. Using the lexicographic heuristic, each factor is assessed until a factor is found that clearly differentiates the options.

Another reduction heuristic introduced by Simon (1956) is called satisficing, which is meant to be a blend of sufficing and satisfying. When using this heuristic, a decision maker will choose the first solution that satisfies a minimal cut-off level and is perceived as being “good enough” (Shah & Oppenheimer, 2008; Todd & Gigerenzer, 2000). When using heuristics in which more than one factor might potentially be assessed, the problem solver still has the decision as to the order in which factors should be considered. This problem has been studied by Todd and Giberenzer (2000) who described several ways in which factors might be prioritized for consideration. The ‘take the best’ rule prioritizes a particular factor because of the proven validity of the factor for solving problems in the past. The ‘take the last’ rule starts with factors that were used in

the most recent problem solving event, whether they proved successful or not. The minimalist approach shows no specific strategy for the ordering of factors, but appears to consider them in a random manner.

Both association and reduction type heuristics satisfy the effort-reduction criteria proposed by Shah and Oppenheimer (2008) by reducing the number of factors, often to only one, so that integration of less information is necessary. By reducing the number of factors, the difficulty of storing their values is reduced (Shah & Oppenheimer, 2008) and the need to compare the value of one factor to that of another is eliminated (Todd & Gigerenzer, 2000).

Fixation. A third heuristic type as classified by Talanquer (2006) is fixation. This involves the tendency of the problem solver to repeatedly use the same strategy even when the nature of the problem changes and another strategy might be more effective. This strategy is reminiscent of the ‘take the last’ rule but is broader than simply starting with the same factor most recently used in a similar problem. Fixation often results in overgeneralization of principles and laws to situations to which they do not apply, or to use the same strategy that worked in a previous situation regardless of any change in the nature of the problem. Furió et al. (2000) seem to be describing this same heuristic when referring to ‘functional fixedness’ which occurs when students over-generalize the use of a particular explanation. An example of this is shown by the overuse of Le Chatelier's Principle to explain every change in an equilibrium. Talanquer (2006) also refers to functional fixedness, but sees it as a sub-category under the general fixation category. He describes functional fixedness as the tendency of students to interpret models and

symbols in a literal manner without recognition of their limitations. Using a functional fixedness mindset, a student might interpret a 2-dimensional Bohr model of an atom as having electrons that travel in circles around the nucleus.

Empirical Assumptions. In addition to domain specific knowledge and heuristic strategies, chemical explanations can also be influenced by the problem solver's conceptions about the nature of the world or their empirical assumptions (Talanquer, 2006). While there are a range of assumptions that chemistry students typically have about the nature of the world (Talanquer, 2006), given the context of the problems that will be explored in this study, 'teleological', and 'essentialism' type thinking are most relevant.

Teleological reasoning occurs when the cause and effect of an event are confused, so that the consequence of an event is posited as the cause through the lens of intentionality or purpose (Kelemen, Rottman, & Seston, 2013; Talanquer, 2007). It was classically illustrated in the Aristotelian view that the explanation for natural phenomena was best given with reference to their essential purpose or "final cause" rather than looking for a mechanistic explanation that described the events leading up to the phenomena and their relationship to it. As previously discussed, mechanistic/causal explanations in chemistry can be constructed by referring to the structural features and interactions of various particles. These interactions are summarized by general principles, or laws that predict the direction of the interaction but do not explain it. When an explanation is constructed by using only the principle or law, omitting any reference to the underlying interactions, a teleological explanation will very likely be the result

(Talanquer, 2007). In chemistry, the teleological assumption can be described as the idea that substances have a natural or predetermined state that they will try to achieve (Taber & García-Franco, 2010). The desired state is usually associated with a law or principle. In the area of periodic trends, the rule that students appeal to most often is the ‘octet rule’. This will be described in depth in the next section. Students often exhibit fixation in their use of this simple explanation by ignoring limitations as well as actual causes for any transformation and discussing the purpose using anthropomorphic terms.

The essentialism assumption is seen when students believe that substances have an essential character or underlying nature that is the invisible causal mechanism for various properties or changes (Gelman, Coley, & Gottfried, 1994; Talanquer, 2006). This essence is retained even if the substance assumes differing forms. A student might maintain that sodium is reactive because that is part of its nature. Both teleological and essentialism assumptions set the stage for simplified reasoning strategies (heuristics) that guide the student in the problem solving process.

The literature shows that student problem solving can be described in part by their domain specific knowledge, the use of certain heuristics, and that some of the heuristics are influenced by empirical assumptions about the nature of the world. There is also evidence that many students rely on recall and intuitive guessing when their knowledge is limited (Salame et al., 2011; Wang & Barrow, 2013). When this is the case, students may give no explanation for their responses.

Student Understanding and Explanations of Periodic Trends

This section focuses on a review of the literature specific to periodic trends. Studies directed towards periodic trends rarely focus on student reasoning strategies, but sometimes strategies did emerge as part of the findings. For example, Eymur et al. (2013) studied high school students and preservice science teachers in Turkey to determine the alternative conceptions that participants held about atomic size (radius). They used an eight-question, multiple-choice instrument that accessed the students' conceptions concerning the relative size of the radius for various groups of atoms and ions, and found that many high school students and preservice teachers believed that the nuclear charge was the sole factor that determined the size of an atom. This seems to be an example of a very simple one-reason strategy where no additional factors were considered. While nuclear charge is important, it is not the only determinant of atomic or ionic radii. Other students expressed the idea that a higher positive charge made an ion larger, or that the size was determined by the period or group number itself. These are examples of students using an association type heuristic without any further justification. While the misconceptions generated by this study were very interesting, since the responses were suggested in the questionnaire rather than generated solely by the participants, it suggested a need for a more in-depth analysis to determine the actual thought processes that students were using to come up with their explanation choices. Another study (Salame et al., 2011) conducted in an urban four-year college in the United States, also addressed atomic radius. Through the combination of an open-ended question and interviews, the authors determined that most students relied on rote

memorization or simple guessing to determine atomic size. While the interview method was more effective in eliciting the reasoning used by students, it was limited in scope by the use of only one periodic trend.

A series of studies on ionization energy (Taber, 1998; Tan et al., 2008, 2005; Tan & Taber, 2009) revealed several reasoning strategies that students commonly use to predict periodic trends. A multiple-choice ionization energy instrument developed by Taber (1999) was used in various settings to validate the representative nature of the research results. They found that the results were consistent in all of the settings where the instrument was used, and that the primary misconceptions expressed by students could be classified under the headings of octet rule, stability of full and half-filled shells, and conservation of force. The octet rule, which is found in most textbooks (Talanquer, 2007), states that atoms have a tendency to gain, lose, or share electrons until they have a total of eight in their valence shell. While the octet rule does not state that atoms ‘want’ or ‘need’ eight electrons, this is the idea that students quickly internalize and may never fully replace even after acquiring more scientifically appropriate explanations (Kelemen & Rosset, 2009). This is an example of teleological thinking in that it postulates that atoms have a natural state of eight valence electrons that they try to achieve. Kelemen (1999) asserts that teleological reasoning is a fundamental aspect of human thought and as such can be suppressed, but not completely erased. For this reason, the octet rule as well as the closely related ideas concerning the special stability of filled and half-filled shells, become firmly entrenched in the minds of many students even after being exposed to more scientifically appropriate reasoning involving particle and force interactions.

Unlike the octet rule that describes a general tendency concerning the behavior of atoms, the conservation of force concept actually distorts electrostatic principles in a subtle manner that appeals to students' intuitive desire for simplicity. Rather than integrating the effect of nuclear attraction, electron repulsion (which varies between core and valence electrons) and the average distance of valence electrons from the nucleus, conservation of force thinking allows the student to simply compare the number of electrons and protons. If there are more protons, then each electron experiences a larger portion of a set amount of force. Conversely, if there are more electrons than protons, there will be less attractive force to share between the greater numbers of electrons. In a study of 450 high school and university students from five different countries including the United States, 38% chose the answer that "when an electron is removed from the sodium atom, the attraction of the nucleus for the 'lost' electron will be redistributed among the remaining electrons" (Tan et al., 2008, p. 270). The percentage of students from the United States affirming this answer was 54%. Conservation of force is classified as making use of the additivity heuristic that falls under the general association type heuristic as shown in Table 2.1.

Taber (1998) speculates that the conservation of force idea may originate when the learner misinterprets what was read in textbooks, heard in the classroom, or from a misunderstanding of prerequisite topics. He also suggests that there might be some intuitive bias which leads to this particular misinterpretation. Taber noted that none of the students claimed to have been taught to reason using conservation of force. In a later study of graduate level preservice chemistry teachers in Singapore, Tan and Taber (2009)

found that the preservice teachers exhibited conservation of force reasoning at a slightly higher percentage than the comparison high school students. Since these preservice teachers go on to teach chemistry, it suggests that some students are learning conservation of force reasoning in the classroom because their instructors have taught it.

Wang and Barrow (2013) studied the conceptual frameworks held by students when explaining phenomena in the areas of periodic trends, chemical bonding, molecular shape and polarity. The study was conducted with undergraduate chemistry students in the United States and involved interviews of six students, three identified as having a lower level of chemistry expertise and three with a higher level. The study found that the lower level students saw the periodic trends as a set of rules to be memorized and did not seem to understand the role of positive nuclear charge in their explanations. This can be compared to the study conducted by Eymur (2013) which found that many students used the number of protons as the sole predictor of atomic size. It is unclear from the Eymur study if students understood the role that the protons play in determining size, or if it was used only as an associative heuristic. In the Wang and Barrow study (2013), the lower level students had misconceptions regarding both energy levels and electrostatic forces while the higher level students had more sophisticated atomic models, understood electrostatic forces and used them in their explanations. While the high level students had a good understanding of prerequisite concepts, they still relied heavily on the octet rule to justify trends in reactivity, in agreement with previous research by others (Taber, 1998).

Chapter Summary

This chapter reviewed the literature on student reasoning particularly as it pertained to periodic trends. To understand student reasoning concerning periodic trends, it was necessary to form a broader picture of reasoning and problem solving in general. The literature suggests that finding an optimal solution to a problem is a complex process of identifying appropriate factors, assigning a value to each, weighting or prioritizing certain factors, integrating the information, and finally arriving at a solution. The problem solving process is both facilitated and constrained by the content knowledge of the problem solver (domain specific knowledge) and by the use of short-cut strategies (heuristics).

This chapter focused on these two constraints. In the area of domain specific knowledge, three concepts were found to have core significance in the area of periodic trends: atomic structure, electrostatic forces within the atom, and the ionization process. The second constraint concerning reasoning strategies or heuristics commonly used by chemistry students was also reviewed. Using Talanquer's (2006) review as the starting point, it was found that students frequently use associative, reduction, and fixation type heuristics to simplify the problem solving process. Students also use heuristics based on teleological or essentialism empirical assumptions. These heuristics are effective at simplifying the problem solving process, but are often not effective in helping the student to supply a scientific explanation. Since simplified strategies do sometimes enable the student to reach a correct solution, the strategies can be resistant to change.

Finally, student explanations in the area of periodic trends were reviewed. It was found that students seem to gravitate toward the reduction, or one-reason type heuristics when explaining trends in atomic radius. When explaining ionization energy, the teleological heuristic utilizing the octet rule and the additivity heuristic utilizing the concept of conservation of charge misconception predominated. None of the studies reviewed included the breadth of periodic trends included in the present study, nor did they specifically explore how the students would respond when asked to deal with an unfamiliar problem.

The present study looks at undergraduate students with a range of ability levels to determine how they apply the domain specific understanding that they have about atomic structure, forces, and the ionization process to their explanations of the periodic trends of atomic radii, ionic radii, ionization energy, and reactivity. Their reasoning strategies will be identified and the consistency with which they use particular strategies will be considered. Finally, the present study compares the reasoning strategies used by students as they explain both familiar and unfamiliar periodic trends. In the next chapter, details regarding the study's design, participants, data collection, and method of analysis is provided.

CHAPTER 3: METHODS

This chapter details the methodological approach used in the present study.

Following a description of the methodology will be a description of the context in which this study took place, followed by details concerning data collection and the analysis techniques that were utilized.

Methodological Approach

The following research questions, which guided the data collection and analysis phase of this study, are listed below.

1. *What are the types of reasoning strategies used by undergraduate general chemistry students in their explanations of periodic trends including atomic radii, ionic radii, ionization energy, electronegativity and reactivity?*
2. *How does domain specific knowledge concerning atomic structure, electrostatic forces operating within the atom, and the ionization process shape the reasoning strategies of undergraduate general chemistry students in regard to the above trends?*
3. *What effect will an unfamiliar periodic trend problem have on the reasoning strategies utilized by undergraduate general chemistry students?*

The use of a qualitative approach, utilizing rich description of student thought processes, was seen as most suitable to obtain the answers to these questions. The strength of qualitative methods lie in their inductive approach and emphasis on descriptions rather than numbers (Maxwell, 2013). While qualitative research methods do not provide information that can be used to predict and control behavior, they do provide

understanding of the way people make sense of the world around them, which can be especially valuable to educators (Sjöström & Dahlgren, 2002). The qualitative framework to be used is a modified form of phenomenography which is defined by Marton (1986) as “mapping the qualitatively different ways in which people experience, conceptualize, perceive, and understand various aspects of, and phenomena in, the world around them” (1986, p. 31). The present study looked at the ways in which undergraduate students perceived and understood the implications of the periodic organization of elements, as embodied in the periodic table, on various periodic trends. The focus, however, was not on students’ perceptions of the content related to the periodic trends, but in the explanations that they supplied. By focusing on reasoning strategies rather than the content, this study departs from the normal phenomenography focus. However, by focusing on reasoning strategies, especially in relationship to domain specific knowledge, much can be learned about why students construct the specific conceptions that they do.

The primary outcome of phenomenographic research is a categorization of the various ways in which a phenomena may be conceived and the structural framework within which the categories exist (Marton, 1986; Sjöström & Dahlgren, 2002). The present study categorized the various reasoning strategies used when explaining periodic trends, and the circumstances that seemed to favor the use of those strategies. The focus of a phenomenographic study is not the individual participant, but, according to Marton (1986), it is the “pool of meanings” (p. 43) that are embedded within the quotes that are being examined. The individual utterances are grouped according to similarities and then each category is clearly differentiated from all others. Marton (1986) goes on to say that

phenomenography has the capacity to help disclose conditions that facilitate a change from one way of thinking to a better perception of reality. By gaining a better understanding of student reasoning strategies, it should be possible to help students perceive and utilize more effective strategies, and also to begin to more fully integrate their domain specific knowledge into their scientific reasoning.

Participants and Setting

The data for this study was collected in a General Chemistry I course, the first in a two-semester sequence, at a private, four-year college. The college is located approximately twenty-five miles outside of a major city in the Midwestern United States. General Chemistry I covers introductory topics including chemical formulas and equations, types of chemical reactions and reaction energy, stoichiometry, atomic structure, periodic trends and properties of gases, while General Chemistry II covers molecular polarity and intermolecular forces, chemical kinetics, equilibrium, and other more advanced topics. Both courses include three days of lecture plus a 100-minute lab each week. The course textbook is Chemistry: The Central Science (Brown et al., 2014) which was used in conjunction with Mastering Chemistry, an online homework system. Chemistry I is offered during both Fall and Spring semesters. The only prerequisite for the course is the successful completion of two years of high school algebra or an ACT Math score of at least 20.

The classes in which the participants for this study were enrolled included a mix of nursing, education, and exercise science majors, as well as a few students taking the class to fulfill their general education science requirement. Class size did not exceed 30

students for either of the sections in which the participants were enrolled. The research data was collected from Fall of 2016 and Spring of 2017 courses that were taught by the researcher of record. As the only chemistry instructor in a small college, the researcher had complete control of the curriculum design and instructional methods.

Volunteers were recruited by an email invitation, as well as an in-class announcement. The only constraints were that all volunteers be at least eighteen years of age and be registered in the course. A small amount of extra-credit (less than 1% of the final grade) was awarded as an incentive to facilitate recruitment of volunteers. Seventeen students volunteered and participated in the interviews, and from these seventeen interviews, thirteen were selected to be included in the study. The interviews that were selected were primarily from the first group of students that were interviewed in Fall of 2016.

The volunteers were chosen to approximate a maximal variation sample based on semester grade (Creswell & Plano Clark, 2010; Patton, 2001), in order to represent a diversity of reasoning approaches (see Table 3.1). This type of sampling is able to capture the uniqueness that is characteristic of diverse individuals, but can also identify any common themes that arise from that diversity (Patton, 2001). It can be contrasted to extreme case sampling in which extreme cases are sought out. In this study, extreme cases as represented by an unsatisfactory grade (D or F) were not represented. While several students in this category were interviewed, they were not included as they relied almost entirely on memorization and had difficulty expressing any type of reasoning at all, making them too extreme to yield useful information (Patton, 2001). The Spring 2017

interviews were collected primarily to supply more examples if needed, however only one was used as they did not seem to add anything unique to those that had already been transcribed and it was felt that the sampling criterion of redundancy as described by Lincoln and Guba (1985) had been achieved.

Table 3.1

Participant Demographic Information

Pseudonym	Declared Major	Semester Grade
Corban	Exercise Science	B-
Karla	Nursing	A
Katie	Exercise Science	A-
Krissy	Nursing	A
Loni	Nursing	A
Macy	Nursing	C+
Monica	Psychology	C
Nathan	Elementary Education	A-
Rhonda	Nursing	C
Robert	Nursing	C+
Sandy	Nursing	B-
Sonya	Nursing	B
Tina	Nursing	B

Background on the Periodic Trends Unit

The chemistry course in which this study was conducted, covered the topic of periodic trends about four weeks before the end of the semester. Data was collected after completion of the unit in the two weeks following the unit exam. Prior to the unit on periodic trends, the students had been exposed to a unit on atomic structure, quantum numbers, and electron configuration. About seven class sessions were devoted to the topic of periodic trends. This included information about the trends in atomic and ionic radii, effective nuclear charge, ionization energy, electron affinity, and general trends

among metals and nonmetals. Individual group trends were not covered. The unit was taught using several group activities that utilized inquiry worksheets to enable students to construct conceptions concerning the topic, interspersed with short lectures, and quick-response assessments. The phrase ‘octet rule’ was never used by the instructor, nor the idea of a special stability of full and half-filled shells. Instead, electrostatic forces, as governed by Coulomb’s Law and energy principles, were emphasized.

Data Collection

Several data sources were used in this study including the Atomic Structure Student Evaluation (ASSE), audio recordings of semi-structured interviews, and students’ unit exam results for the course. These were collected over the last four weeks of each semester in which the study was conducted. Table 3.2 gives the dates on which this data was collected.

Table 3.2

Data Collection Timetable

Date Range	Data Collected
11/17/2016	ASSE
11/18/2016	Unit Exam
11/22/2016 – 12/13/2016	Interviews
04/18/2017	ASSE
04/21/2017	Unit Exam
04/26/2017 – 05/04/2017	Interviews

Interviews. The focus of all three research questions involved the identification of the reasoning strategies used by students. This was addressed through the use of semi-structured interviews, the preferred method of data collection in phenomenographic

studies (Marton, 1986; Ornek, 2008; Sjöström & Dahlgren, 2002), using a “think-aloud” protocol (Bowen, 1994). The interviews ranged from 25-50 minutes depending on the students’ willingness to talk and the number of follow-up questions used to clarify answers. The interviews were audio-recorded and then transcribed verbatim. Pseudonyms were assigned to each participant in an effort to maintain confidentiality.

Interview questions were first developed after consulting two pre-existing instruments: the Atomic Size Diagnostic Instrument (Eymur et al., 2013) and the Ionization Energy Diagnostic Instrument (Tan et al., 2005). Since both of these instruments were constructed as multiple choice instruments with a limited scope, they were used only used as guides to stimulate thinking. Open-ended questions were developed that included questions concerning atomic structure, forces, the ionization process, periodic radius trends and ionization energy trends. This protocol was used in the pilot study conducted in April 2016 and can be found in Appendix A. After conducting the pilot study, the following changes were made in the ASSE and interview protocol:

- Four questions concerning high school chemistry background were added to better understand what may have affected the students’ understanding beyond the current course.
- Questions regarding domain specific knowledge (DSK) were separated from questions about trends. The DSK questions were primarily in the ASSE while the questions asking about periodic trends were all placed within the interview. This was done to be able to ask more detailed questions in the

ASSE about atomic structure without making it longer. The interview still included some clarification and elaboration of the DSK questions that were asked within the ASSE, but had a greater focus on the periodic trends.

- The following periodic trends were added: Ionization energy in a group, ionization exceptions, second ionization energy for an atom that had at least two valence electrons, electronegativity, and reactivity of metals. The additional questions allowed the researcher to more easily see patterns in the data. The reactivity trend was added to see how an unfamiliar question influenced student reasoning.

Table 3.3 shows the revised interview protocol. These questions were used in all interviews along with additional clarifying questions as needed.

Table 3.3

Interview Questions

Background Questions
1. What type of chemistry experience did you have prior to the current Chemistry class you are enrolled in?
2. Approximately how long ago was it?
3. Please describe your feelings about that previous chemistry experience.
4. Do you remember learning about periodic trends in the previous class?
Periodic Trends Questions
5. Please explain your drawing of sodium. Imagine you could see the sodium atom or visualize it. Is there anything that you chose not to show in your drawing that you would like to describe further?
6. How does your orbital diagram relate to your picture of the sodium atom?

7. Rank the following atoms in order of increasing atomic radius and explain your reasoning. Na, Mg, S, K [Students were specifically asked about the radius trend in a group and in a period if this was not explicit in their answers.]
 8. Is there any difference in the radius between the neutral sodium atom and the sodium ion? Explain.
 9. How is the radius affected when fluorine atom becomes fluoride ion? Explain.
 10. On the Atomic Structure Student Evaluation, it was explained that the first ionization energy is the amount of energy needed to take away **one** electron from an atom. Would you please identify and explain the general trend in first ionization energy as you go down a group?
 11. What is the general trend in first ionization energy as you go from left to right in a period? Explain.
 12. The trends in ionization energy are not as regular as the trends in atomic radius. There are some exceptions as shown in this graph (see Appendix B). The general trend across the period is an upward trend. The elements boron and oxygen are exceptions.
 - a. Think aloud about reasons that might cause boron to require less energy to lose an electron than expected.
 - b. Think aloud about what might cause oxygen to require less energy to lose an electron than expected.
 13. The second ionization energy is the energy needed to remove a second electron from an atom. How would this energy compare to the first ionization energy for potassium? For calcium? Explain.
 14. Electronegativity is the tendency of an atom to attract electrons in a bond as shown in the picture (see Appendix B). Could you predict and explain any trends for this property?
 15. Using the chemical reactions and information found in the chart, (see Appendix B) attempt to explain the decreasing trend in reactivity of the period four metals potassium, calcium, and iron with water.
 16. Try to explain the increasing reactivity of Li to K with water as you go down the group.
-

The second research question, about the relationship of DSK to reasoning strategies was addressed by using a combination of the ASSE, selected questions from

the unit exam (Appendix C), and the interview data. The ASSE used in this study was an open-ended instrument consisting of seven questions used to elicit both explanations as well as student-drawn representations. Questions about atom structure and orbitals, intra-atomic forces, as well as ion formation were included in the instrument. The instrument that was used in the pilot study can be seen in Appendix D. The instrument was changed after the pilot study, as previously described, and the final version is shown in Table 3.4 (without spaces left for answers). This instrument, in conjunction with the exam questions, was intended to help ascertain whether a participant had an adequate DSK to predict the various periodic trends.

Table 3.4

Atomic Structure Student Evaluation (ASSE)

ASSE Questions
<ol style="list-style-type: none"> 1. Draw a representation (picture) of a sodium atom. <ul style="list-style-type: none"> • Show all subatomic particles in their correct locations relative to each other, and name them (you may use a key to identify particles). • Identify the charge if there is one on all subatomic particles. 2. Use your picture to identify “valence electrons” and describe what a valence electron is. 3. Use your picture to identify “core electrons” and describe what a core electron is. 4. <ol style="list-style-type: none"> a. Describe or define an atomic orbital. b. How many orbitals would be needed for all of the electrons in the sodium atom? c. Show a labeled orbital diagram for sodium (using boxes for each orbital with arrows to illustrate the electrons). d. Could an electron in a 3s-orbital of sodium ever be closer to the nucleus than an electron in a 2s-orbital? Explain. 5. Describe the attractive and repulsive forces within an atom.

6. a. The term ionization energy is the amount of energy needed to take away one electron from an atom. Write a chemical equation that shows this process for sodium.
b. If this occurred for sodium, how would your atomic picture change?
 7. Imagine a picture of a fluorine atom. How would the picture change when the fluorine (F) becomes a fluoride ion (F⁻)?
-

Data Analysis

This section describes the data analysis procedures used to answer each of the research questions. Table 3.5 serves as a summary of the overall plan for the analysis of the data with alignment to the research questions.

Table 3.5

Analysis Overview by Research Question

Research Question	Data Sources*	Analysis
What are the types of reasoning strategies used by undergraduate general chemistry students in their explanations of periodic trends including atomic radii, ionic radii, ionization energy, electronegativity and reactivity?	Interviews	<ul style="list-style-type: none"> • Determine frequency of each reasoning code
How does domain specific knowledge concerning atomic structure, electrostatic forces operating within the atom, and the ionization process shape the reasoning strategies of undergraduate general chemistry students in regard to the above trends?	ASSE Exam Interviews	<ul style="list-style-type: none"> • Assess DSK in each of the DSK domains • Determine distribution of codes by adequate/inadequate DSK
What effect will an unfamiliar periodic trend problem have on the reasoning strategies utilized by undergraduate general chemistry students?	Interviews	<ul style="list-style-type: none"> • Compare coding for reactivity with overall frequency determined by question one • Determine consistency of reasoning between reactivity and all other trends

*ASSE = Atomic Structure Student Evaluation

Analysis of reasoning strategies. The answers to all three research questions hinged on the identification of student research strategies. The identification of these strategies made use of the student interview data. The coding unit selected for the analysis of reasoning strategies was the entire explanation that a student gave for a specific periodic trend in either a group or a period. It was possible for several codes to be assigned to one periodic trend explanation if there were several different aspects of a student's explanation that each demonstrated a different reasoning type. Because the students were asked to think aloud, at times their thinking changed directions as they tried out various ideas or they combined strategies to form their complete explanation.

In the coding process, individual interviews were coded one at a time rather than going through all of the interviews and coding one trend at a time. This decision was made because sometimes the students' thinking would continue into the following trend, and important aspects would be missed by looking at only one trend in isolation. Analysis of the interviews began by first reviewing the transcripts holistically, to become familiar with the data, correcting any transcription errors, and recording overall impressions concerning student understanding and general reasoning strategies.

Once an overview of the transcripts was complete, coding could commence. In phenomenography, codes are usually determined by identifying the most significant elements in each coding unit (Ornek, 2008; Sjöström & Dahlgren, 2002), grouping these elements and allowing the codes to emerge. This practice was observed in the pilot study with the result that five codes were identified. On the basis of the holistic review of the interviews as well as the results from the first three students coded, the original five codes

were broken down into more specific codes, using names that had been proposed by previous researchers in the heuristic and scientific reasoning literature (Evans, 2006; Kuhn, Iordanou, Pease, & Wirkala, 2008; McClary & Talanquer, 2011; Simon, 1990; Talanquer, 2006) along with a few code names that originated with the researcher of record. This process is outlined in Table 3.6. Five additional reasoning strategies emerged in the same early coding period that had not been recognized in the pilot study, but that had been previously identified in the literature, including analogical (Dunbar & Klahr, 2012), essentialism (Gelman et al., 1994), proportional (Lamon, 2012), and representativeness (Shah & Oppenheimer, 2008). The last code that did not stem from the pilot study was the no-reason/memorization code that was needed for any student that offered either no explanation or simply stated that they had memorized the trend.

Table 3.6

Development of Codes for Reasoning Strategies

Pilot Study Code	Coding Definition	New Codes that Emerged	Comments
Availability	When explanations are chosen based on familiarity or cognitive accessibility.	Availability – No change Similarity	Both are association codes (Talanquer, 2006), with similarity focusing on a similar feature in both cause and effect.
Additivity	When the student thinks that the attractive force from the nucleus is conserved and equally distributed to all electrons.	No additional codes added	
Integrated reasoning	When the reasoning strategy is analytical in nature, integrating several factors involving structure or forces to predict an outcome.	Multi-variable reasoning (later changed to multi-factor reasoning. Analytical reasoning Analytical partial Analytical failure	Multi-variable reasoning focuses on the integration of several factors while analytical reasoning focuses on the ability to see inconsistencies and revise thinking.
Functional Reductionism	When the student reduces the complexity of the reasoning by reducing the factors considered.	One-reason Satisficing Lexicographic	The one-reason strategy focused on the most appropriate factor that is then justified, while satisficing focused on the use of a less appropriate factor. Lexicographic reasoning considered several factors, but did not integrate them.
Teleological	When the student referred to an atom wanting a full shell, or to be like a noble gas.	No additional codes added	

These codes were provisionally defined using the definitions from the literature (see Table 3.7) and all previous coding was reviewed. As coding continued, some coding definitions were refined to fit the unique context of the study. The coding rules underwent a final revision at the end of the first round of coding and before the second round began. Table 3.7 provides a summary of all codes, the literature definition, and the final coding rules that were used in the study.

Table 3.7

Definitions for the Reasoning Strategy Codes

Reasoning strategy code	Definition followed by rules for use
Additivity	<ul style="list-style-type: none"> • When a student thinks that effects are equally distributed among the parts of a system (Talanquer, 2006). • Used for the conservation of force idea that if there are more protons than electrons, each electron gets to share a larger portion of the attractive force as though it were a fixed quantity.
Analytical	<ul style="list-style-type: none"> • Critically evaluating an initial heuristic response through a slow and controlled process (Evans, 2006). • When a student is able to see inconsistencies, weigh ideas and revise explanations to reach a conclusion based on logical reasoning.
Analytical-failure	<ul style="list-style-type: none"> • Defined for this study to denote when a student uses contradictory reasoning and is not aware of it.
Analytical-partial	<ul style="list-style-type: none"> • Defined for this study to denote when a student uses contradictory reasoning, is aware of it, but is either unable or unwilling to resolve the tension and change the response.
Analogical	<ul style="list-style-type: none"> • Used to form a bridge between what is already known and what is being explained (Dunbar & Klahr, 2012). • The student compares the problem situation to some other more familiar situation and uses the comparison to facilitate thinking and explain causes.

Availability	<ul style="list-style-type: none"> • Causes are chosen based on their familiarity or cognitive accessibility (Talanquer, 2006). • The student considers a factor that is unjustified or irrelevant to the situation, but which is very familiar, easily available, or which was recently used in a different context, but which is now unwarranted.
Essentialism	<ul style="list-style-type: none"> • The idea that objects or substances have an inherent essence that causes the properties we see (Gelman et al., 1994) • The student explains a trend by referring to the general character or essence of the element.
Lexicographic	<ul style="list-style-type: none"> • When factors are considered one at a time until a specific factor differentiates between alternatives (Fishburn, 1974; McClary & Talanquer, 2011). • Redefined for this study as when a student discusses several factors, then chooses one as the basis for a decision and discards or minimizes the rest without justification.
Multi-factor	<ul style="list-style-type: none"> • Originally termed ‘multi-variable’, this applies when all factors are taken into consideration to predict whether they will affect the outcome in an additive or interactive manor (Kuhn et al., 2008) • Redefined for this study to apply when a student looks at how two or more factors jointly influence an outcome.
Multi-factor failure	<ul style="list-style-type: none"> • After consideration of several factors the decision to defer any choice is made. This is prevalent when the comparisons make a choice too difficult (Dhar, 1996) • When a student attempts to weigh multiple factors, but ends up in confusion either because of a lack of ability to weigh competing factors or when the trend is known, feels that none of the factors considered gives a compelling explanation of the known result and so fails to endorse any explanation.
No reason – memorization	<ul style="list-style-type: none"> • The student can offer no answer or responds that they memorized the trend.
One-reason	<ul style="list-style-type: none"> • Almost any property is seen as being caused by only one factor (although the factor may change depending on the property) (Talanquer, 2006). • Redefined for this study to apply to any student who used the one, most appropriate factor and justified its use.

Proportional	<ul style="list-style-type: none"> • When assertions concerning direct and inverse proportions are made and appropriately justified (Lamon, 2012). • When a student discusses how the increase or decrease in forces affects the properties in question.
Representative-ness	<ul style="list-style-type: none"> • Judging whether a target object (situation) belongs to a particular type or class (Shah & Oppenheimer, 2008). • If the student recognizes the relationship of electronegativity or reactivity to ionization energy and uses this relationship to explain trend.
Satisficing	<ul style="list-style-type: none"> • Solves a problem by picking the first satisfactory alternative when many alternatives are available (Simon, 1990). • Redefined for this study as when a student is satisfied with using only one (possibly two) factor(s) to explain a phenomenon, ignoring others that either oppose the conclusion or are vital to the context.
Similarity	<ul style="list-style-type: none"> • When it is assumed that the cause and effect in a causal relationship have similar features (Talanquer, 2006). • If a student takes an adjective such as large, and thinks if it applies to one characteristic such as charge, than some other characteristic must also be large without applying a scientific principle such as electrostatic forces to explain it.
Teleological	<ul style="list-style-type: none"> • If a student asserts that a phenomena changes in response to some internal purpose (Talanquer, 2006). • When the student refers to the atom wanting a full shell or subshell, or wanting to be like a noble gas.
Fixation	<ul style="list-style-type: none"> • The tendency of the student to use the same strategy even when the nature of the problem changes and another would be more effective (Talanquer, 2006). • Used as a summary of a student's responses. This code should be applied when a student uses the same argument that focuses on a single factor to explain more than 50% of the trends.

During the coding revision process, four heuristic codes from the literature (one-reason, satisficing, multi-factor, and lexicographic) were redefined to more accurately fit the context of the study. This was done in response to an early problem which was encountered when trying to establish clear boundaries that would differentiate the satisficing and one-reason heuristics since both reduce the number of factors considered.

Satisficing, as defined by Simon (1990) occurs when a person picks the first satisfactory solution that meets a pre-established expectation based on prior experience. The problem solver does not attempt to search all of the alternatives to find a solution. The primary thought is that the problem solver does not persist in searching for the one optimal solution. The satisficing heuristic was redefined for this study as being used when the student ignored factors that were vital to the problem solution. The one-reason heuristic was then redefined as an explanation that uses the one most appropriate factor and includes a reasonable justification for why that factor was appropriate. The student using the one-reason heuristic may have been aware of other contributing factors and chosen to ignore them, or they may have had no understanding of these other factors. An example of the one-reason strategy can be seen when looking at the explanations for the trend in electronegativity when going down a group as given by Monica:

I'm going to say that the highest attraction is at the top and the lowest is at the bottom because the ones at the top has stronger forces. . . .

They're closer to the nucleus so the attraction is stronger.

This excerpt was coded as one-reason because the predominant factor controlling the attraction of electrons to the atom is distance. Attraction decreases as distance from the nucleus increases. An example of satisficing was shown by Nathan's explanation for the same trend:

I believe the trend would increase as you go down the periodic table because there would be more attractive forces. Yes I believe it would

have a greater pull as you're going down because there would be more protons.

This is an example of satisficing because while it is true that as the number of protons increase, the attractive forces will also increase, Nathan ignored both repulsion from increasing core electrons and the increasing distance of bonding electrons from the nucleus. He was satisfied to look at only one factor and to ignore others that would have also had a significant influence on the trend and led to the opposite prediction.

The multi-variable reasoning strategy as defined in the literature (Kuhn et al., 2008) was both renamed and redefined. The literature definition of multi-variable reasoning is that all variables are considered, as well as the manner in which they interact, in order to predict an outcome. It was renamed as multi-factor reasoning because the term “factor” has been used consistently throughout the study rather than variable. It was redefined for the present study to apply to students who considered how two or more factors jointly influenced an outcome, without leaving out any major contributing factor. This change was made to highlight students who were progressing in the sophistication of their thinking in that they were able to integrate the effects of more than one factor even when at times there might have been additional factors not mentioned.

There were instances where satisficing might also have appeared to be multi-factor reasoning if the boundaries between the terms had not been carefully defined. An example of how distinctions were made between satisficing and multi-factor coding can

be seen by looking at the following quote by Corban when he explained the changes in ionization energy within a group:

If there's more shells there's going to be repulsion, like between the inner-most shell and the shell next to it. So this one [sodium] isn't close, even remotely close to the eleven protons, so there's going to be little attraction between the protons and the electrons on the way out. In lithium, there's only two orbitals, so it has two orbitals, one inner, and there's one valence electron [in outer shell]. It still is going to be closer to the nucleus rather than the one electron in sodium.

Corban discussed sodium having more orbitals than lithium, and that more orbitals caused more repulsion. He then went on to state that sodium is larger (in radius) than lithium (probably due to the repulsion factor that he started with). Corban links distance and repulsion, two appropriate factors which interact to affect the final prediction, but he fails to explain the causal factor that would modify the results of repulsion, thus he was not coded as multi-factor. Instead, he was coded as satisficing, because he ignored a factor (increased nuclear attraction) that would negate the effect of the increased repulsion that he did discuss.

The last code that was redefined was lexicographic. The literature definition (Fishburn, 1974; McClary & Talanquer, 2011; Svenson, 1979) is that the problem solver looks at factors one by one, often in order of attractiveness or importance, comparing their values, but stops as soon as a factor helps in differentiating between alternatives. This presented a problem in the interviewing situation because the student would often start with the factor that differentiated between the alternatives and ignore those that were

the same, even when aware of them, which resulted in a one-reason code. The lexicographic code was redefined as referring to the student that considered several factors, but settled on only the one that seemed most attractive as the basis for a decision and appeared to discard the rest. This is not the same as the student that was able to discuss the effect of interactions between various factors in making a decision (multi-factor reasoning). An example can be seen in the explanation that Nathan gave for the decreasing ionization energy going down a group. He stated:

More protons would have an effect in the sense of drawing electrons towards it in the center. . . . Well, also as you go down the periodic table, you get more core electrons. And so with more core electrons, there's more of a repulsive force that's going to push. It's going to push those outer electrons away, so making it easier to pull one away when there's more forces pushing out.

Nathan correctly assessed the effect of proton attraction and electron repulsion and knew that the effect was opposite. Since he had memorized the trend, he simply ignored the effect of the protons and decided that the repulsion from core electrons was the reason for the decrease in the trend. He never explained why the attractive force from the protons did not counterbalance the repulsion from the core electrons, but rather seemed to dismiss the attraction argument.

After the final coding rules had been established and the first round of coding was complete, it became clear that many of the students exhibited a consistency in the flow of their explanations, using the same limited factors and justifications for many of the

periodic trends. The fixation code (Talanquer, 2006) was instituted in order to reflect the totality of the students' explanations rather than a single isolated reasoning strategy. This heuristic describes the tendency of students' to overgeneralize the use of a particular rule or principle regardless of any change in the problem context. Fixation was coded for any student using the same factor and justification for at least 50% of the periodic trends.

The first round of coding was completed by the researcher of record with the collaboration of a second researcher who had several years' experience teaching undergraduate chemistry. The second researcher participated in about one-third of the coding, deciding on codes independently and then collaborating until consensus was reached. As a part of this collaboration, coding definitions were reviewed and refined as discussed previously, until the final definitions were arrived at by the end of the first round of coding. A second round of coding occurred in which the researcher of record reviewed all codes that had been assigned, flagged any questionable codes, and then collaborated with the second researcher until agreement occurred. Lastly, explanations with the same code were compared to each other to ensure consistency. The code assignments continued to be evaluated until it was felt that no further questionable codes were being found.

After coding was complete, and the frequency of code utilization had been compiled, a decision was made to simplify the results by eliminating five codes from any further analysis. The first code to be eliminated was proportional reasoning. Proportional reasoning could be defined as the ability to compare two quantities using a mathematical justification involving direct or inverse proportions (Lamon, 2012). All of the periodic

trends depend on a correct interpretation of Coulomb's Law which governs the forces between charged particles and is expressed mathematically as $F \propto q_1 q_2 / r^2$; where F = Force, q is equal to either the total positive charge of the protons or the negative charge of an individual valence electron, and r is the distance between the protons in the nucleus and an average valence electron. Correct explanations for all of the trends are dependent on a combination of the direct and inverse squared relationships found in this equation. While the students were shown this equation during the course of instruction, and the relationships were explained, no student referred to the equation explicitly. Instead they used the relationships found within it, such as the relation that force decreases with distance. This can be seen in a statement by Karla regarding the ionization energy in a group when she said:

The energy required gets smaller because the energy levels are getting bigger and they're getting further away from the protons . . . so the protons don't have as much attraction to the first electron that's being taken away.

Karla was explaining that when the distance between the protons and the outer electrons is larger, the force will in turn get smaller. She did not refer to Coulomb's Law, but she did see an inverse type relationship between distance and force. Some students may have had an intuitive idea that distance had a greater effect than charge, but no one referred to the inverse squared relationship as the reason. While all students relied on an implicit type of proportional thinking, none of them used explicit mathematical terminology. Because of the universality of this implicit form of proportional thinking, a decision was made to exclude it from the present study.

Four additional codes were eliminated because of their infrequent use. A decision was made to eliminate any code that was used by less than five people if it also had less than seven references. The combination of these requirements ensured that the eliminated codes were not an important feature of student reasoning in this study. The following codes met this criteria and were eliminated from further analysis. They are listed in order from least (one) to most (six) references: literalism, analytical, analogical, and analytical failure. The analytical code was not only used infrequently, but was difficult to distinguish from multi-factor reasoning, so the two codes were in effect merged.

Once the codes were established, and the interviews underwent several rounds of coding, the results were compiled in several ways to allow patterns to emerge. The codes were compiled by student, total frequency, periodic trend, DSK of the student using the code, and by familiar versus unfamiliar trend. This allowed an assessment of the relationship of DSK to specific reasoning strategies, and a comparison of the consistency of reasoning strategies when the level of familiarity of the problem was changed.

Analysis of DSK. The first step of analysis, necessary for research question two, was to assess student understanding in each of the three DSK areas as either adequate or inadequate in the domains of atomic structure, electrostatic forces within the atom, and the ionization process. The data included the combined evidence of the unit exam, ASSE questions, as well as the portion of the interview that occurred before questions concerning periodic trends were posed. The criteria for determining adequate DSK are shown in Table 3.8.

Table 3.8

Criteria Used to Assess Students' DSK

Topic	DSK needed to predict periodic trends	Assessment instrument and question number*
Atomic Structure	<ul style="list-style-type: none"> • Is able to draw a correct Bohr representation of an atom. • Is able to construct correct electron configurations and orbital diagrams. 	ASSE 1 E 1, 2, 5, 6 I
Forces	<ul style="list-style-type: none"> • Can describe what gives rise to attractive and repulsive forces • Can differentiate the effect of core and valence electrons in shielding outer electrons from the nucleus, or can use the concept of effective nuclear charge. 	ASSE 5 E 3 I
Ionization Process	<ul style="list-style-type: none"> • Is able to correctly describe the meaning of ionization energy • Can produce a chemical equation that represents the ionization process. • Can differentiate first and second ionization energy 	ASSE 6a-b E 4, 7 I

*ASSE = Atomic Structure Student Evaluation; E = Unit Exam; I = Interview

The criteria for adequate DSK concerning atomic structure was that students needed to understand the Bohr model of the atom in order to predict most trends, but when explaining the exceptions to the ionization energy in a period, they also needed to understand the orbital structure that is part of the quantum model (Taber, 2003b). After the pilot study, it was determined that an understanding of the wave properties of the atom was not important at the level of student reasoning expected.

The criteria for understanding the electrostatic forces within the atom was based on the principles of Coulomb's Law about attractive and repulsive forces (Taber, 2003b).

Students needed to understand that protons attract electrons, electrons repel other electrons, and core electrons cause more nuclear shielding by their repulsion than the valence electrons (Wang & Barrow, 2013).

The criteria for the ionization process was based on the concepts that would be needed to predict the different periodic trends that related to ionization energy. This included an understanding of the definition of ionization energy as well as being able to represent the ionization process using a chemical equation.

Trustworthiness

Dual role of instructor and researcher. As mentioned previously, the researcher of record also served as the instructor for the course. As the instructor of the general chemistry course at the institution where the present study took place for the previous seven years, the researcher had both understanding and control over the instructional setting ensuring that every participant in the study had been exposed to the same content and instructional activities. This type of prolonged engagement by the researcher with the students had the potential to encourage the establishment of rapport and trust (Guba & Lincoln, 1989) so that students might feel less hesitation in proffering their ideas and explanations. Evidence for this sort of trust was seen when 29% of the students in the course volunteered for the pilot study done in the Spring of 2015, at a very busy time in the semester, when no extra credit was offered. Hammersley (2006) suggests that the established relationship between an instructor and students also has the potential to enhance the depth of data collected.

The disadvantage of the dual role of instructor and researcher is the possibility of introducing bias by creating expectations for the type of reasoning that individuals might use based on past performance. To guard against this bias, the interview transcripts were thoroughly reviewed several times, with a critical attitude concerning any previous interpretations. When there was any uncertainty about the interpretation, the second researcher was brought into the decision-making process to discuss alternative interpretations and arrive at a consensus. If the meaning of a particular explanation was unclear, it was compared to other explanations made by the same student to gain insight into the student's understanding and mindset. While it is not possible to eliminate all bias, significant effort was made to interpret the results in a manner that truly reflected the data collected.

Another possible disadvantage of the dual role of instructor/researcher is that the instructor had a position of power in the relationship with students which might cause the students to feel that their participation status could influence future treatment in the course. This threat was minimized by the clear assurance conveyed during the invitation process and just before the interview took place, that participation was voluntary and would have no bearing on the instructor's attitude or interactions with the student in the future.

Limitations. Inherent limitations of qualitative studies dependent on interview data are the level of participant motivation (Maeyer & Talanquer, 2013; Sjöström & Dahlgren, 2002) and willingness of participants to verbalize their thought process due to either verbal ability or comfort level (Taber & Bricheno, 2009). Given the low-stake

nature of the task, and the time investment that was required, the possibility that students might not choose to utilize the same degree of cognitive effort as they might on an exam was real. While the low-stake nature of the task had the potential to decrease the frequency of more sophisticated reasoning, the present study showed a large number of students that were willing to explore multiple avenues of thought even though they were not always able to come to a decisive conclusion. In the present study, some students were better able to verbalize their thoughts than others. In order to put students at ease, the interview started with general conversation unrelated to chemistry, then progressed to background questions that were easily answered before the more difficult questions began. The students were given as much time as they needed and assured that the focus of the study was not the correctness of their answers, but their thought process, or the way that they explained their ideas. While some students did show slight signs of nervousness, most seemed very willing to cooperate to the best of their ability to verbalize what they were thinking.

This study does not attempt to exemplify the typical undergraduate student experience in general chemistry. As in many qualitative studies, the value lies in the rich description rather than in the sample size or representativeness of the sample. While the sample selected included a diversity of ability levels as reflected by semester grades (excluding only those with unsatisfactory semester grades) in order to see a range of reasoning types, it was composed primarily of female, nursing students. In addition, the results from this study are merely a snapshot taken in a specific context and at one point of time within the semester. It is not expected that the results from this one setting will

exhibit generalizability to all undergraduate students, but it is expected that aspects of this study will resonate with the experience of other instructors and the results will provide information that will be useful as they attempt to understand the reasoning patterns of their students and the role that these patterns play in the students' ability to construct understanding of chemistry topics.

Credibility of analysis. In a phenomenographic study the basis of credibility lies in the relationship of the data obtained in the interviews to the categories or codes used to describe the student experience (Ornek, 2008; Sjöström & Dahlgren, 2002). This was shown primarily through the use of excerpts from the interviews in support of the codes and through a rich description of the evidence for those codes, confirming and resolving any areas of disconfirming evidence, and through the auditing efforts of the second researcher (Creswell & Plano Clark, 2010). It was also done by carefully delineating the methods used in the analysis as this chapter has attempted to do. The use of several data sources in the determination of DSK increased the level of credibility by enabling some degree of triangulation.

In the next chapter, the findings of the analysis described in this chapter are elaborated upon. First the types of reasoning strategies that had the greatest influence on student thinking is described. Then the relationship between the most influential reasoning strategies and domain specific knowledge are explored. Finally, student reasoning in response to an unfamiliar problem is discussed to determine how student reasoning is affected.

CHAPTER 4: FINDINGS

This chapter will present and interpret the findings of this study. As a reminder for the reader, the research questions that guided this study were:

1. **Reasoning Strategies:** *What are the reasoning strategies used by undergraduate general chemistry students in their explanations of periodic trends including atomic radii, ionic radii, ionization energy, electronegativity and reactivity?*
2. **Domain Specific Knowledge (DSK):** *How does domain specific knowledge concerning atomic structure, electrostatic forces operating within the atom, and the ionization process shape the reasoning strategies of undergraduate general chemistry students in regard to the above trends?*
3. **Unfamiliar Trend:** *What effect will an unfamiliar periodic trend problem have on the reasoning strategies utilized by undergraduate general chemistry students?*

The first section presents an overview of the types of reasoning strategies that were used by students to explain various periodic trends. The second section explores the relationship between domain specific knowledge (DSK) and specific reasoning strategies. The third section will investigate how patterns of reasoning are affected when an unfamiliar problem is presented. All student names are pseudonyms.

Research Question 1: Reasoning Strategies

This section addresses the frequency and distribution of reasoning strategies used by students in explaining periodic trends as summarized in Figure 4.1. The focus of the section is on those reasoning strategies with the highest frequency of utilization having at least 30 coded references, as well as those strategies that were used primarily for one

trend. It was found that those codes with at least 20 references were broadly used for many trends, whereas, the majority of the codes that had between seven and twenty coded references were restricted to only a few periodic trends.

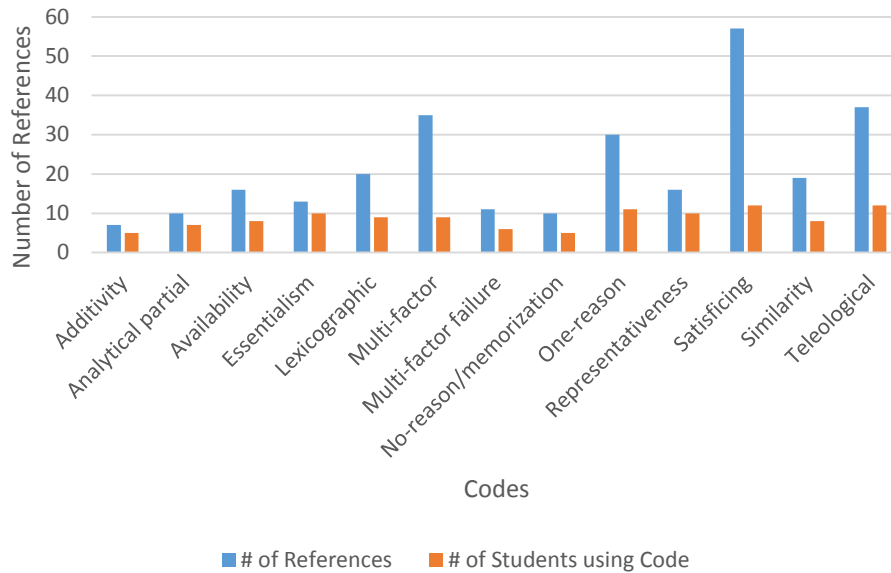


Figure 4.1. Reasoning strategies used by thirteen students to explain periodic trends

Most frequently used reasoning strategies. While a wide variety of reasoning types were used, four stood out as being of particular prominence. The four most frequently used reasoning strategies in this study in order of decreasing frequency were satisficing, teleological, multi-factor, and one-reason. This is not surprising as each of these strategies, with the exception of teleological, could be considered useful, in explaining any periodic trend.

Satisficing. Satisficing is a blend of the words sufficing and satisfying (Gigerenzer & Goldstein, 1996), and occurs when a person picks the first satisfactory explanation that will solve the problem rather than searching for the optimal solution (Simon, 1990). In this study, the satisficing heuristic was redefined as the type of

reasoning used when a student was satisfied to use one primary factor that did not adequately explain the periodic trend while ignoring other more scientifically appropriate factors that either opposed their conclusion or were essential to fully explain the trend.

Satisficing was the most frequently coded heuristic in this study with 57 coding references out of a total of 291, or roughly 20% of the codes. Twelve of the thirteen students in the study used satisficing at least one time. This result is consistent with the singularity, relevance, and satisficing principles postulated by Evans (2006) that people consider a single hypothetical possibility at a time, choosing what they feel to be most relevant in the current context and will accept it if it seems satisfactory, often without any additional validation. The solution is usually chosen by means of an implicit process that requires only shallow processing of context requirements. This implicit processing competes with more explicit processing that considers all relevant factors and carefully works through their scientific justification.

Satisficing was often used to code a student who referred to either attractive or repulsive forces but did not balance their explanation with an assessment of the opposing force. This was considered to be a partial explanation that biased whichever force was most convenient in providing an explanation for a prediction the student had already decided on. Two examples illustrate how students used this reasoning strategy to validate a prediction. The first was Corban's explanation as to why the atomic radius increases in a group:

So at this group, between orbitals, the repulsion is going to get larger . .
. so if you have more orbitals, then the repulsion between the electrons
in the orbital is going to get larger and larger.

Corban used electron repulsion but ignored the compensating factor of increased nuclear attraction that also occurs.

Ronald also used satisficing when explaining his incorrect prediction that electronegativity will increase as you go down a group. He stated:

As you keep going down, the number of protons in there would be
increasing. Those two electrons would be more prone to go towards
that nucleus full of more protons.

Unlike Corban who used only electron repulsion, Ronald was satisfied to only look at the attractive forces and failed to consider the repulsive forces that also increase going down a group.

One-reason. The one-reason heuristic strategy was the fourth most frequently coded response. It is similar in nature to satisficing, occurring when any change in a system is seen as being caused by a single factor (although different changes are caused by differing single factors) (Talanquer, 2006). When using this type of reasoning, the student did not discuss other competing factors that might have affected the problem being solved. Because both one-reason and satisficing responses usually rely on a single factor, the decision was made that if the one factor used by the student was indeed the most scientifically appropriate factor to use, the student would be coded as using a one-

reason strategy. For example, Krissy used a one-reason strategy when explaining the changing radius of atoms within a group. She stated:

I know that it increases in size as you go down the periodic table
because you're increasing the energy levels which means that each
energy level makes it bigger.

The size of orbitals in higher energy levels is the primary reason for the increase in radius even though other factors such as increasing attraction from protons which is opposed by increasing repulsion from core electrons each have an effect. While only providing a single factor explanation, the explanation provided by Krissy was scientifically justifiable, unlike the previous examples of satisficing. When using either the satisficing or one-reason heuristics the student chooses to consider only a single factor, which places a lower demand on cognitive processing, enabling the student to reach a conclusion faster and with less effort (Verschueren, Schaeken, & d'Ydewalle, 2005).

Multi-factor. Multi-factor thinking was the third most frequently coded reasoning strategy. Multi-factor thinking demands the highest level of processing capacity, as the ideal multi-factor explanation would take into account all relevant factors, explaining each and showing how they jointly affect the outcome in question in either an additive or interactive manner (Kuhn et al., 2008). The high frequency with which students used both the satisficing and one-reason heuristic strategies suggests that the students preferred strategies that required less cognitive processing. Thus, it was surprising to see the relatively high frequency of multi-factor thinking.

In this study, 35 responses were coded as multi-factor out of 291, or roughly 12% of all codes. Nine of the thirteen students used multi-factor thinking at least one time. An example of multi-factor reasoning is shown in the following interview excerpt by Karla when she discussed the change in ionization energy across a period:

It takes the most energy in the top right corner, and that's because as you're moving across a period, you have the same amount of core electrons. . . . So you know the effective nuclear charge is getting bigger, and so the protons have more attraction on the electrons. So they are like holding on to them tighter, or pulling them closer, and because of that, because the protons are so much, outnumber the core electrons, because the core electrons are staying the same, it takes a lot more energy to take away an electron. So that's why as you move across a period, they're gaining protons, but keep the same amount of core electrons and so the ionization just gets bigger and bigger.

Karla used two ideas: proton attraction, and core electrons. She wove them together to give the concept of effective nuclear charge. While she did not explicitly discuss electron repulsion in this trend, she gives a more complete explanation of effective nuclear charge later stating: "The effective nuclear charge is increasing as you go to the right. The positive charge has more attraction than there is repulsion between the electrons." She then related effective nuclear charge to the energy required to overcome that attraction and take away the electron. She was the only student in the study who was able to both explain and use the concept of effective nuclear charge. This is a complex property that takes into account the total nuclear attraction as well as the electron repulsion. Since the

majority of the electron repulsion is due to the core electrons, rather than the valence electrons, effective nuclear charge is often simplified to the number of protons minus the number of core electrons.

Teleological. Teleological reasoning was coded with the second highest frequency with 37 of the 291 responses or about 13% being coded in this category. Twelve of the thirteen students in the study used teleological reasoning at least once showing that it was a major part of their thinking about this topic. Teleological reasoning involves an inversion of cause and effect, such that the effect of a change is seen as the purpose which drives the change to occur, as described in Chapter 2. The explanation might reference a chemical principle or rule without explaining the interactions that cause the principle to work. In this study, teleological reasoning was coded whenever the student described the atom as needing to fill the outer shell, subshell or orbital, fulfill the octet rule, or trying to become like a noble gas. A fundamental human bias toward teleological thought as proposed by Kelemen et al. (2013) is supported by the almost universal use of the full shells explanation by students in this study. Some examples of how these ideas were expressed are given below:

It's just because everything wants to be filled. So this is like if magnesium has eight [electrons] but has just one valence electron, it's going to be more willing to just want to lose that electron. (Corban on the second ionization energy of magnesium.)

If you take the next one [electron] from that full orbital, then that would want, it doesn't want to give it away so it would take more ionization energy to get it. . . .

Because it [electron] wants to stay with all the valence electrons. Once it [potassium ion] has a full set, it doesn't want to give them away, it wants to just keep them. (Tina on the second ionization energy of potassium.)

Because the attraction between the nucleus and electrons are strong because atoms want to become fully shelled, like have all the electrons in the shell. They want to become a noble gas so they're less likely to release the electrons so they're going to pull them in closer. (Katie on the atomic radius in a period.)

While an important goal of science instruction is to encourage the development of scientifically sound, causal reasoning, one must still ask whether there is any positive function that teleological reasoning might fulfill. Talanquer (2007) suggests that teleological explanations can be useful in chemistry particularly when a general rule predicts directionality in the transformation of a chemical system. A teleological explanation takes complex chemical systems with many interactions and simplifies them in a way that allows students to more easily organize their knowledge around major concepts, giving them a powerful means with which to make predictions (Taber, 2003b; Talanquer, 2007). The octet rule provides a useful rule of thumb to determine the number of electrons that must be transferred or shared in a chemical reaction because it is straight-forward and easy to remember (Tan et al., 2008).

The utility of teleological reasoning involving the octet rule can be seen in several of the interviews when students were initially undecided about a trend, but the octet rule helped to steer their thinking in productive directions. When discussing the ionization energy in a period, Ronald initially predicted that it would decrease as you go from left to

right – an incorrect prediction. As he started to think about it however, he changed his mind and explains his reasoning as follows:

I'm just thinking right here, next to the noble gases, how this is a charge of negative one [the charge of a fluoride ion]. That's always ready to gain one electron. . . . I think that [fluorine] will require more energy to take one [electron] away from that because just by its very nature you're trying to fight what it wants to do. . . . I feel like it's similar to the logic that goes down the increasing atomic number would have an increase in protons so you'd have more forces acting on the electrons as you keep going along because the numbers get larger either way you go.

Ronald started with an incorrect prediction, but corrected himself as he remembered that atoms tend towards a noble gas configuration, which means that elements in group 17 tend to gain an electron. If they normally gain an electron, it is reasonable that it would require more energy to lose one. He then was able to construct a more causal/mechanical reason involving proton attraction.

A similar pattern of reasoning occurred to Corban when explaining the electronegativity in a period.

I think if you [go] left, electronegativity is going to increase because if you say, you look at sodium compared to sulfur. . . . But it goes against the fact that sodium wants to lose an electron because it only has one valence electron but sulfur has six. . . . I guess electronegativity is going to want to increase. . . . It's just the fact that in the whole outer shell everything wants to be filled. So if you

have six valence electrons rather than just one, there's going to be closer to the amount of eight electrons that must be filled and then the one valence electron, this will take seven electrons to get filled rather than the two needed here.

Again, Corban made an incorrect prediction initially but was able to correct his thinking by using a full shell teleological rational. Unlike Ronald, he did not add any additional reasons involving forces.

While teleological reasoning utilizing the octet rule may be a necessary instructional simplification of a complex topic, there are dangers inherent in its use. The generalization of the tendencies governing particulate behavior overlooks the limitations and exceptions to the rule, and often masks the true nature of the interactions that are occurring (Taber, 2009; Talanquer, 2007). Students find the rules so easy to apply that they overgeneralize their use, leading to incorrect ideas and conclusions. This occurred in the present study as illustrated by Katie when she discussed the second ionization energy of calcium:

With calcium, if you follow the same logic, it would take more energy, the first ionization, because once it has already lost an electron, it will have an alkali metal configuration and at that point, it wants to lose that valence electron to get the noble gas configuration. So it will be easier to take the second electron versus taking the first one where the atom will just simply become an alkali metal configuration.

Katie came to an incorrect conclusion regarding the relative magnitude of the second ionization energy compared to the first. Her entire argument was based on the goal of an

atom to achieve a noble gas configuration or full shell. Since calcium is able to achieve the noble gas configuration only with the loss of the second electron, she determined that the energy would be less for the second electron than the first since the loss of the first electron achieves a configuration that does not involve a full shell. She had a bias toward the teleological octet reasoning even though she realized that it was contradictory to the argument she had used previously for the second ionization of potassium where she discussed the increased attraction of protons. After giving her teleological argument for calcium, she stated, “Proton logic is not helping me here,” tacitly acknowledging her previous explanation for potassium. Corban used an identical teleological argument for the second ionization energy trend stating:

Magnesium already lost one electron. I guess the ionization energy would be less than its first ionization energy because it just has one valence electron outside instead of two. . . . Everything wants to be filled. So this is like if magnesium has eight [electrons] but has just one valence electron, it’s going to be more willing to just want to lose that electron.

In other cases, the use of teleological reasoning may not have resulted in an incorrect prediction, but it was overgeneralized and misapplied to a situation in which its use was not warranted. Such was the case in the following excerpt in which Ronald was trying to explain why beryllium required more energy to lose an electron than boron. He first noticed that in the valence shell, boron had two electrons in the s-orbital, and only one in the p-orbital.

Just having one electron in that energy level will make a huge difference because you'd only be pulling away, acting on the one electron in there. I mean you'd be fighting however many, the five protons that are in there, but there's only one electron in that energy level. . . . Once it's full [the 2s-orbital/subshell] it's harder to pull away [the electron].

In this situation, the decrease in energy for the removal of the 2p-electron is not because it is by itself in an orbital. There is actually less repulsion when the electron is not paired which would tend to increase the amount of energy needed to remove it. The decrease in energy for ionization is instead related to the increase in the energy of the 2p-orbital relative to the 2s. Ronald has overgeneralized the full shell rule to include subshells as well as shells and he disregards the fact that the atom will not achieve the octet of electrons or a noble gas configuration. Six other students used an identical argument for exceptions to the general ionization trend. Karla used a similar argument when thinking about the electronegativity in a period. She stated:

If you look at lithium, it only has one electron in that energy level, in 2s, and so it wants to fill up that one. So I feel like lithium would attract electrons more than beryllium will.

She then began to consider the radius and effective nuclear charge and decided to reverse her prediction to the correct one. In this case, while her first intuitive reasoning was teleological, when given the time to reflect, she was able to generate a more scientifically correct causal/mechanical reason. This does not mean that she saw the error of applying the full shells argument to subshells, but that in this case she recognized overriding

factors that caused her to change her prediction. Loni also used an argument regarding the stability of a full s-orbital when describing the reactivity of atoms in a period. The widespread use of the overgeneralization of full shells to full subshells or orbitals lends support to the appeal that the teleological octet argument has for students.

Reasoning strategies associated with specific trends. While satisficing, multi-factor, one-reason and teleological strategies were used most frequently in part due to their more general applicability to all of the periodic trends, there were other heuristics that seemed to be more uniquely applied to only one or two of the trends, as seen in Figure 4.2.

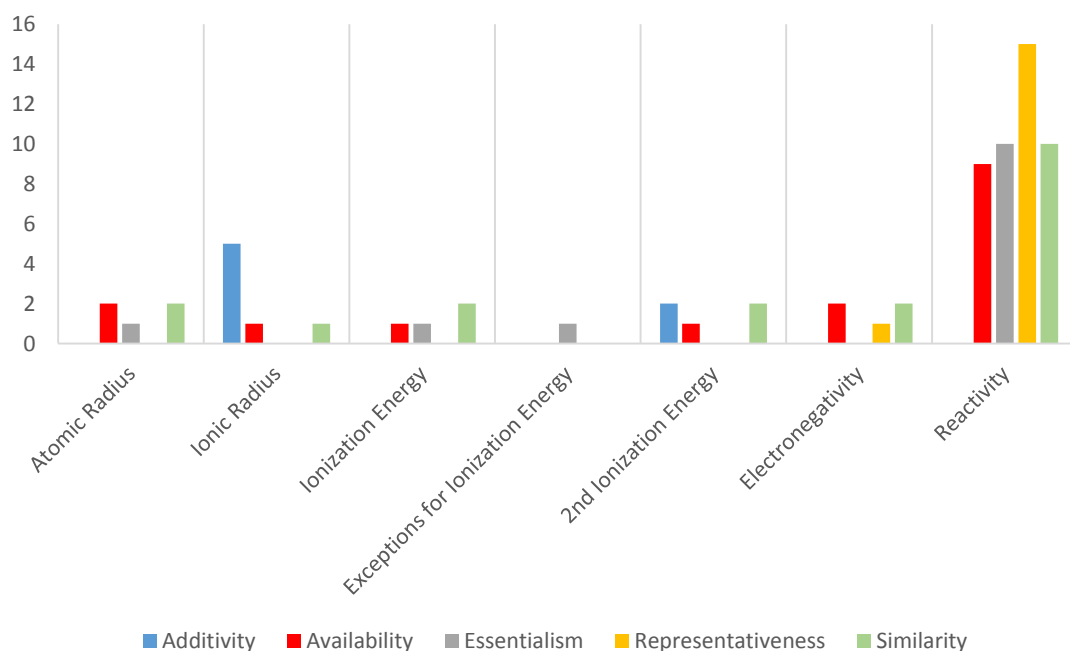


Figure 4.2. Heuristics associated with specific trends.

Additivity, availability, essentialism, representativeness, and similarity were each used primarily for one trend, rather than being more evenly distributed as the other

heuristics were. Of these, additivity was used primarily in explaining ionic radius, while all of the others were used in explaining reactivity. Both additivity and the heuristics associated with reactivity are described in the following section.

Additivity. Additivity is shown when a student reasons that properties of a system are evenly distributed among the individual components (Talanquer, 2006). In the context of periodic trends, additivity reasoning was shown when students assumed that all protons carry a set amount of attractive force that is divided equally among the valence electrons. This application of additivity reasoning is commonly used by chemistry students and has been called the “conservation of force” misconception (Taber, 1998, 2003b, 2003a; Tan & Taber, 2009; Tan et al., 2005) because students conceive of nuclear force as a conserved quantity and use the idea to successfully predict trends involving ionization. The limited applicability of the additivity heuristic to trends involving the ionization process helps to explain why it was primarily used to explain trends in the ionic radius.

An example of additivity can be seen in Sonya’s explanation of the second ionization energy of magnesium.

When you take away an electron, but the protons are still the same amount, you have that positive force to pull it in and then there’s less electrons that’s repelling the positive force and so when you try and take away that next one, there’s a greater force on that single electron because that one electron that was taken away previously, the force that was on it is now transferred to the rest of them, like it’s

spread out and so there's a greater pull from the nucleus on that next electron to get it away.

Katie used a similar explanation for the radius increase that occurs when fluorine gains an electron to form the fluoride ion.

It will become larger because it's gaining an electron but has the same number of protons and so, then the attraction between a proton and an electron will be slightly lesser because the proton has to attract more electrons.

While Tan and Taber (2009) found that slightly more than half of their participants used conservation of force, less than half (five out of thirteen) of the students in the current study used this type of reasoning for a total of seven references. Compared to the teleological thinking that was almost universal, additivity was much more limited in scope. Part of this limitation was due to the limited applicability of conservation of force reasoning to three of the seven major topics discussed. Another limitation for the use of conservation of force (additivity) reasoning may have been the limitation imposed by a lack of understanding concerning forces, which will be detailed in the section dealing with the impact of domain specific knowledge (DSK) on reasoning strategies. Those students that did not clearly articulate that protons attract electrons (as shown in the next section on DSK) may not have been able to discuss forces meaningfully in any form.

Heuristics used primarily for the reactivity trend. Reactivity was another trend where particular heuristics, specifically availability, essentialism, representativeness, and similarity, predominated. These heuristics were not generally used for other trends.

Reactivity differed from the other trends in that it was the most unfamiliar of the trends and students were provided with a greater variety of resources to support their reasoning. Resources included the periodic table (available for all the questions), chemical equations representing the reactions that occurred, and a table that included the first through fourth ionization energies for all of the elements involved (Appendix B). Both the unfamiliarity and the resources that were available may have had an effect on the types of reasoning used. The unfamiliarity issue will be addressed in detail by the third research question later in this chapter.

Availability. Availability is a type of reasoning based on the familiarity or cognitive accessibility of the causal factors used (Talanquer, 2006). The access to resources available only for the reactivity trend may have influenced reasoning strategies as seen by the increase in the use of factors prompted by the information provided by the ionization table. Nine of the sixteen availability references were coded for the reactivity trend. Availability was coded when a student inappropriately used a factor which was unjustified or irrelevant to the situation, but which is familiar, or readily available in the form of a reference chart. In the case of the reactivity trends, if the ionization chart was used in an inappropriate manner, then the response was coded as availability. Examples of inappropriate use of the available chart occurred in the interviews with several students and usually focused on the jump in ionization energy that occurs after all of the valence electrons have been lost. In responding to the reactivity in a period, Katie initially stated:

I believe that potassium will react, it reacts more vigorously because of the large jumps between the first ionization energy and the second and the third and the

fourth compared to calcium which also has large jumps, but not as large of jumps as potassium. And then iron has very small jumps compared to the other two.

As Katie continued to ponder the question, eventually she was able to come up with a more scientifically appropriate reason, but her first response was based on the availability of the chart and the large change in energy that she saw after potassium lost the first electron. Rhonda used a similar rationale for the reactivity in a period. She said:

Like for potassium, it has a really high jump between ionization energies. Like it's not as big of a jump from ionization energies. . . . It takes a bigger ionization energy from first to second then for calcium or iron. I think that it would make it react more.

It is difficult to determine from this excerpt whether Rhonda understood what ionization energy meant. She was simply using the chart and noticed the large change between the first and second ionization energy for potassium. She may have remembered this as something important from class discussions and so assumed incorrectly that it was the cause of the increased reactivity of potassium. Later Rhonda responded, "It's gaining electrons because it is bonding with the oxygen and the hydrogen." It became clear that while Rhonda knew electrons are involved, she has no real understanding of the process. Sonya and Ronald appropriated almost identical reasoning, not understanding that the reactivity of a metal increases when the ionization energy is low so that the electrons can be more easily lost.

Nathan was also coded as using the availability heuristic when responding to the reactivity trend. His response was interesting as he initially used the ionization chart in a

scientifically appropriate manner, but failing to mention electrons he was asked if potassium had lost an electron in the reaction. His response after considering the equations was, “Potassium has a charge of plus one, H has a charge of [pause] nope, it is not losing an electron.” When asked the next question, which concerned the reactivity in the group, he responded:

You have that chart because it has something to do with the ionization energy. So all I can think of is just that the ionization energy gets less and less as you go down the periodic table, so it becomes, it basically becomes what I would consider less stable in the sense that it is more reactive.

Nathan knew that the ionization chart that was provided must be the key to reactivity, but because he had not yet mastered how to recognize the loss of electrons in an equation, he was left at a loss as to how to explain why the ionization energy was relevant.

While students used availability reasoning most often when responding to the reactivity trend, it was also used with other trends. In Monica’s response concerning the atomic radius trend in a period, she stated:

As you go from left to right in a period, you get larger because the atomic mass grows. . . . As you go from left to right you have more electrons, valence or just electrons in general. Because like say I was at aluminum, I would have three electrons in the last orbital so that could expand the [break in sentence] because you’re taking more space.

Monica used the common sense reasoning that when something has more mass and more particles, it will take up more space rather than a more scientific argument dealing with

the interactions between particles. Her argument had more cognitive accessibility because it works most of the time when assessing everyday objects. Rhonda also used availability type reasoning in describing the atomic radius in a period. She explained:

The atomic radius starts to get bigger. . . . The electrons are moving farther away from the nucleus, there's becoming more of them. . . . There starts to form more shells and so then the electrons are getting farther away from the nucleus.

In this case, the argument sounded scientific, but she was using the term 'shell' incorrectly and reverted to the same argument that she had used for the change in atomic radius going down a group. The primary factor in predicting group radius is the increase in the number of electrons, which then require larger shells to contain them. The number of electrons is no longer as relevant across a period since the number of shells do not change, but for Rhonda, this reason was available because it had been used for the previous trend.

Essentialism. Essentialism, another strategy used most often to explain reactivity trends, occurred when a person assumed that elements or substances have an inherent nature or essence that not only gives the substance its identity, but that causes all of the properties that can be observed and is independent of the substance itself (Gelman et al., 1994; Talanquer, 2006). A student was coded as using essentialism when they explained a trend by referring to the character or essence of the substance without a more specific description of why the substance behaved in a particular way. While this heuristic was used once each for atomic radius, ionization energy, and exceptions to ionization energy, it was used for reactivity in 10 of the 26 responses including both group and period

trends. In spite of the additional resources that were made available for answering the reactivity trend, many of the students were still at a loss to come up with a specific explanation and instead felt that it was caused by some mysterious characteristic inherent to the elements. Although Macy generally used the number of electrons and their role in attracting the nucleus to explain trends, when asked to explain the reactivity trend in a group, she made the very general statement:

I'm guessing it has to do with what kind of element it is, what kind of characteristics it has - its chemical ones.

Monica often discussed either the number of shells needed for the electrons, or how full a shell was in order to explain most trends, however when confronted with the change in reactivity across a period, she instead referred to the type of metal when she stated:

It could be the type of element because iron is a metal, potassium is an alkali metal and calcium is an alkaline earth metal so they have different characteristics.

The use of this reasoning strategy, along with the similarity and representativeness strategies, will be examined with more detail in the section concerning unfamiliar trends.

Similarity. Similarity is the tendency to assume that a cause and its related effect share similar features or attributes (Talanquer, 2006). A student might take an attribute such as 'large' and assume that if one property of the atom is large, then other attributes must also be large without explaining the relationship by applying any scientific principle. Ten of the nineteen responses coded as similarity occurred when explaining the

reactivity trend. An example of the use of the similarity heuristic occurred when Ronald explained the trend in reactivity moving across a period. He stated:

Potassium, it jumps from 419 [kJ/mole] to 3042 [kJ/mole] then another thousand jump . . . That would be the amount of energy that has to be expelled and acted on potassium. . . . Big reactions give off a lot of heat generally or they take away a lot of a lot of heat. . . . There's more heat involved so it becomes hot enough to burn. So I was just thinking that intensity probably comes a lot from how much energy is actually required to pull away that first electron.

Ronald assumes that a large ionization energy (or increase in successive ionization energies) causes the release of a large amount of energy or heat as a result. Rather than thinking about how an increase in required energy needed might increase the difficulty of breaking bonds and slow the reaction down, he has the conception that a large amount of energy at one stage of a reaction must result in a large amount of energy at all stages of that reaction.

Representativeness. The representativeness heuristic was also used primarily to explain reactivity trends. Representativeness thinking is used when students recognize the target problem as belonging to a particular class of problems (Shah & Oppenheimer, 2008). The representativeness code was used primarily if the student recognized the relationship of the trend in question, to the ionization process when it was not ionization energy that they were being asked to explain. Given this requirement, the heuristic could only be used for the electronegativity and reactivity trends. In other words, to use the

representativeness heuristic, the student would need to recognize how the ionization process compared to electronegativity or that ionization is actually the controlling issue in the reactivity of metals. Katie recognized the relevance of the ionization data to the reactivity of metals across a period when she stated:

It [potassium] wants to lose the first electron because it has such a low first electron ionization energy. So, it wants to lose it, the valence electron, so it will react with the water in order to have that exchange. . . . Iron has a very high first ionization energy. So, it means that it doesn't really want to lose the first electron, or at least less so compared to the other two, so it will be less likely to give away that electron and react with the water.

Katie knew that ionization energy (IE) was the energy needed to lose an electron and recognized that the amount of energy required was relevant to the reactivity of metals. She then compared the first IE of potassium to that of iron, made the connection that a lower IE made it easier for an exchange of electrons to occur, and drew the conclusion that a lower IE promoted higher levels of reactivity for a metal with water. Used in this manner, the representativeness heuristic is very useful to the solution of problems when applied appropriately.

Summary for Research Question One. The first research question sought to determine the reasoning strategies used by undergraduate general chemistry students in their explanations of periodic trends in atomic radii, ionic radii, ionization energy, electronegativity and reactivity. This section has highlighted those strategies that were

used with the greatest frequencies as well as those that were particularly important in explaining specific periodic trends. It was found that the satisficing, teleological, multi-factor, and one-reason strategies were used with the highest frequency. Each of these strategies are generally applicable to all of the trends as opposed to the additivity, availability, representativeness, and similarity strategies that were used primarily for a more limited number of trends. A comparison of the one-reason and satisficing strategies showed that they were both very similar in that they relied on the use of primarily one factor which reduced the level of cognitive processing for students, allowing them to use less time to come up with an answer. Although the students were not limited in the time allowed, they still had a preference for these strategies. Many students also used the multi-factor strategy which required a greater level of cognitive processing, as more factors had to be considered and their effect integrated. The teleological strategy was used both with high frequency and by almost all students. It is possible that teleological thinking is a fundamental aspect of human thought (Kelemen, 1999).

Reasoning strategies that were limited to a few specific trends included additivity, used only for trends involving the ionization process, and the strategies of availability, essentialism, representativeness and similarity which were all used primarily with the reactivity trend. It is probable that the unique nature of the problem context which included more resources and which was also unfamiliar to the students affected these choices.

Research Question 2: Domain Specific Knowledge

Overview of DSK by domain. The second research question to be investigated

states, “How does domain specific knowledge concerning atomic structure, electrostatic forces operating within the atom, and the ionization process shape the reasoning strategies of undergraduate general chemistry students in regard to the above [radii, ionization energy, electronegativity and reactivity] trends?” In addressing this research question, a summary of students’ DSK is first presented before connecting DSK to the specific heuristics used by students to explain periodic trends. The DSK of participating students was evaluated as adequate (A) or inadequate (I) in each of the three domains according to the criteria described in Chapter Three (See Table 3.6). Table 4.1 shows the results of this categorization in each of the three domains.

Table 4.1

Summary of Student DSK Related to Periodic Trends

Student	Atomic Structure	Forces	Ionization Process
	Adequate (A), Inadequate (I)		
Corban	A	A	A
Karla	A	A	A
Katie	A	A	A
Krissy	A	A	A
Loni	A	A	A
Macy	I	I	I
Monica	I	I	I
Nathan	A	A	A
Rhonda	A	I	I
Ronald	I	A	A
Sandy	A	I	I
Sonya	A	I	A
Tina	A	I	I

It can be seen from Table 4.1 that there were some students that demonstrated inadequate understanding in each of the three areas assessed. Of the students assessed

with inadequate understanding, three students had trouble with atomic structure, six with forces, and five with the ionization process.

Issues caused by inadequate understanding of atomic structure. Atomic structure had the largest number of students demonstrating an adequate understanding, with only three students being classified as inadequate. Understanding of atomic structure was demonstrated by atomic drawings of sodium and by several orbital diagrams and electron configurations on both the Atomic Structure Student Evaluation (ASSE) and the unit exam. An adequate student drawing would use a Bohr representation showing 11 protons and neutrons in the nucleus, and 11 electrons arranged in a circular pattern with two in the first ring, eight in the second and one electron in the third. The protons would be marked positive and the electrons negative. An adequate response for electron configurations and orbital diagrams would consistently show correct electron placement in orbitals and subshells. Students were still classified as having adequate understanding for their atomic drawing if they failed to show the nuclear particles but could describe them in the interview. Figure 4.3 shows the atomic drawings of three students with inadequate understanding of atomic structure. None of these three students showed any of the nuclear particles. Ronald was able to describe the nuclear particles during the interview, however both Macy and Monica demonstrated a lack of clarity about which particles were in the nucleus, or even if some electrons also resided in the nucleus.

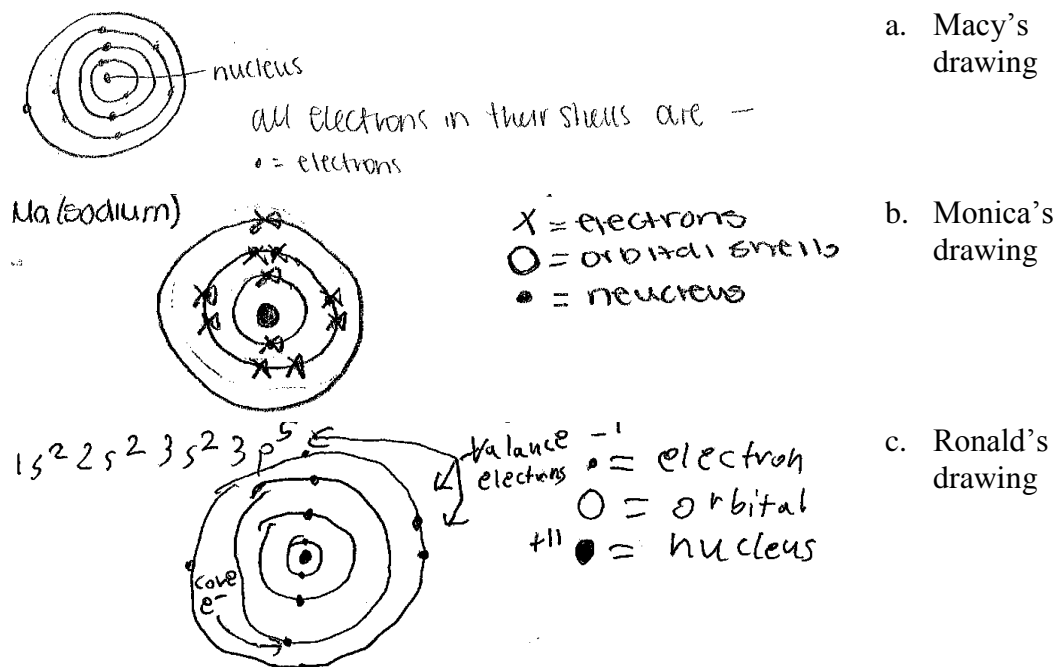


Figure 4.3. Sodium atom drawings that helped to determine the level of understanding of atomic structure.

Inadequate understanding of nuclear particles can be expected to limit students' use of nuclear attraction when discussing periodic trends. For example, while Macy did discuss the attraction of electrons to the nucleus, she emphasized the role of the electrons and failed to take protons into account as shown in her explanation for the decrease in atomic radius from left to right in a period:

Because there is more electrons as you move from left to right, so I know that protons in the nucleus attract more to the more electrons that there are, it's going to pull in so the atomic radius is going to be smaller.

Monica also showed indecision about the nucleus. She stated that, "Protons are positive possibly and neutrons are negative, I'm not sure." When describing periodic trends, Monica never used the term "proton" in any explanation. This also suggests that

an inadequate understanding of atomic structure impacted a student's ability to explain periodic trends. Ronald however seemed to have complete clarity as to the composition and charges within the nucleus even though his picture did not show any nuclear detail, and he used protons in the majority of his explanations.

Each of the drawings in Figure 4.3 differ in respect to electron placement. In both Ronald and Macy's drawings, all subshells were shown as a separate circle or energy level. Macy correctly allocated the electrons to subshells, while Ronald did not. Macy's understanding of the subshell structure enabled Macy to consider subshells when explaining the exception to the trend in IE when going from beryllium to boron. As part of her explanation, she drew a representation that showed subshells and stated, "You're in a different shell [subshell]. . . . In boron there's going to be one [electron] out here by itself so it's going to be easier to take it away."

Ronald also split the energy levels into subshells and had the correct number of electrons, but appeared to be unaware of the 2p subshell which resulted in five electrons in the outer subshell. He consistently exhibited problems allocating electrons in electron configurations or orbital diagrams. Even though Ronald was inconsistent in his placement of electrons in subshells, he was also able to use his understanding of subshells to explain the IE exception from beryllium to boron:

It [last electron to be placed] jumps to a new energy level [subshell] when you hit boron. . . . It would rather lose it. . . . It's closer to the other atom.

It is unclear if Ronald's problems with electron placement affected his periodic trend reasoning in any significant way or only reflected a lack of attention to detail.

Monica's drawing depicted only the principle energy levels or shells, and correctly placed all electrons. This reflects Monica's tendency to consider only the principle energy level in her explanations. While Monica did construct an accurate orbital diagram for sodium in the ASSE, she never referred to individual orbitals during the entire interview and only used the phrase "orbital shells" to mean principle energy levels rather than considering subshells or individual orbitals. This was illustrated when Monica correctly explained the smaller radius that results from the formation of a cation:

Because it loses the electrons, so this third orbital shell goes away
because it only had one electron. So now it only has two orbital shells.

So there's not another electron taking up that space.

It is possible that Monica's reluctance to consider the more detailed electron placement into subshells and orbitals was due to a shallow understanding of the meaning and significance of orbitals.

All three students with an inadequate understanding of atomic structure showed inconsistencies in their ability to construct accurate electron configurations while all students classified as adequate in this domain consistently constructed accurate electron configurations. Since explanations for the exceptions to the ionization energy (IE) trends were based on the placement of electrons in individual orbitals, students with an adequate understanding of atomic structure should have been better equipped to give scientific explanations. Student performance for the two trends entailing IE exceptions can be seen

in Table 4.2. Contrary to expectations, the performance of students classified as having an inadequate understanding of atomic structure was not much different than those students who showed an adequate understanding when explaining the exceptions to IE.

Table 4.2

Students Giving an Accurate Explanation for IE Exception Trends

DSK – Atomic Structure	Total students	Be to B Exception	N to O Exception
Adequate	10	2	4
Inadequate	3	2	0

As seen in Table 4.2, two of the three students with an inadequate DSK in the domain of atomic structure were able to explain the exception in IE from beryllium to boron which is a higher percentage of students than those with adequate understanding. For this explanation, it was only necessary to know the number of electrons in the 1s and 2s subshells. Five of the ten students with adequate DSK in atomic structure also described correct electron placement in subshells, but only two of these students gave a scientific explanation, while three used a teleological explanation based on full subshells.

Adequate DSK in atomic structure did seem to give some advantage to students when explaining the IE trend for nitrogen and oxygen. This trend required that students be able to accurately place each electron in an orbital and recognize that nitrogen has no paired electrons, while oxygen has one paired set. The paired electrons experience repulsion and are more easily lost. None of the students with inadequate DSK in atomic structure were able to give a scientific explanation for this trend. Four of the students with adequate understanding were able to explain that the added repulsion was the key factor causing a lower IE for oxygen. Karla explained it as follows:

It's because when we go from nitrogen to oxygen, you add an electron that is paired with another one in the orbital. So, of the four electrons, two of them are paired, and two aren't. The two that are paired, they don't want to be paired. . . . They have a negative charge so they repel each other. Because of that, I could have imagined that the last electron that's paired trying to get away from the other one.

Each of the students using scientific reasoning gave an accurate arrangement of electrons in orbitals as part of their explanation, while only two of those who failed to use scientific reasoning correctly described this electron arrangement. Of the three students with inadequate DSK, two made no attempt to represent the electron arrangement, and the third gave an incorrect electron configuration and did not show individual orbitals. These results suggest that for students to be able to use scientific reasoning strategies to explain exceptions to the general trends in IE, they need to both consider electron arrangement in orbitals, and be able to represent it accurately.

Since most students experienced difficulty in explaining both trends dealing with IE exceptions, it is probable that while some understanding of orbital structure was needed, this understanding was not sufficient. An understanding of forces was also needed for the nitrogen to oxygen IE exception and an ability to see how the forces might be affected by differing electron arrangements within the orbitals. Students' DSK with respect to forces is described in the following section.

Issues caused by inadequate understanding of forces. An adequate understanding of the electrostatic forces within an atom should include the ideas that the

electrons are attracted to protons, that electrons repel each other, and that the core electrons (closer to the nucleus) more effectively repel valence (outer) electrons than other valence electrons. Since all of the periodic trends are caused by the forces existing within the atom, inadequate understanding in this area should place limitations on the types of explanations that students could produce. An inadequate understanding of forces was shown by six of the thirteen students (See Table 4.1).

An assessment of the problems students encountered when trying to explain and use the factors that control the electrostatic forces within an atom can be classified into three broad issues: issues regarding repulsion, issues regarding attraction, and the effect that single/paired electrons has on the forces within an atom. Table 4.3 provides a summary of these issues.

Table 4.3

Issues Concerning Forces

Issue	Example
Repulsion	<p>“I’d say when there’s not like, not that force, where there’s not positive and there’s not that great of negative - repulsion.” Macy</p> <p>Rhonda never mentioned repulsion to explain any trend. “Paired electrons cause repulsive forces. They do not want an electron.” Rhonda</p>
Attraction	<p>Cause of attraction: “The number of electrons that there are.” Macy</p> <p>“Attractive forces are when the closest orbitals have electrons that fill the shells allowing a stronger attraction.” Monica</p> <p>Sandy never mentioned attraction to explain any trend. Cause of attraction: “The charge of the protons . . . the greater the charge, the more repulsion there’s going to be.” Sandy</p>
Single/Paired Electrons	<p>“When there is only one electron in a box, it means that it’s more unstable, so it’s easier to pull apart.” Sonya</p> <p>Cause of repulsion: “When they [electrons] don’t match up with each other . . . when they’re not paired.” Sandy</p>

Issues regarding repulsive forces. Macy is an example of a student who had no clear concept of what caused repulsion. When asked to explain the cause of repulsion, she stated:

Repulsive forces happen when there isn’t a full shell. It is less likely to be pulled towards the nucleus.”

Her definition of repulsion as given in Table 4.3 was expressed as “not that force” (attraction) dealing with positive and negative charges. Macy seemed to only understand repulsion as the absence of attraction. Without a clear conception of what repulsion meant, Macy avoided all use of repulsion when attempting to explain periodic trends.

Monica also struggled with understanding repulsion. When asked to explain what caused repulsion within the atom, she responded, “Repulsive forces are when the electrons repel energy given off by the nucleus.” Like Macy, Monica understood repulsion in terms of the absence of attraction when she said that electrons repel energy (attractive forces) from the nucleus. Unlike Macy, Monica came closer to a scientific understanding of repulsion when she attempted to describe the shielding effect caused by core electrons as they repel valence electrons. Instead of describing how electrons repel each other, she thought that electrons were repelling energy from the nucleus that pulled them closer together. Monica used the concept of repulsion in only two of the fourteen periodic trend explanations, one of which concerned the ionization energy in a period where she stated:

Ionization depends on the electrons above it. So if it has two, for example, period two has two electrons like in front of it, so all of the electrons in the second orbital would have the same amount of energy to be taken away because they’re all in the second orbital.

In this statement, Monica is referring to the two core electrons that repel the valence electrons. Rather than understanding this force as repelling however, she pictured the two electrons as removing some of the attractive force, shielding the outer electrons from the nucleus. In this case the term ‘shielding’ which is often used by scientists, may have contributed to the confusion that Monica experienced.

Issues regarding attractive forces. There were two problems that surfaced regarding attractive forces: when a student had no clear conception regarding what

caused attraction, or when the students describing the attraction between protons and electrons did not give protons the prominent role. Those students with no clear understanding of attraction included Rhonda, Sandy and Tina. These student tended to avoid using attraction in their explanations, either resorting to memorization alone, or substituting other factors, often without clear justification, to explain the trend. When explaining the first IE going across a period, Rhonda stated:

I think you would also increase because as you're moving it's moving farther, it's going farther away from the different, like the shells are still getting bigger as you move across the period. I think that since it is still getting bigger, it would still be harder to take one [electron] away. . . . The atom has to work harder to use up more energy when there's more shells for an ion.

Rhonda found it difficult to give a coherent reason why as the number of shells increased, the IE also increased other than some vague notion of having to work harder. Without a clear understanding of attraction, it is not really possible to explain the trend.

While Rhonda avoided using forces of any kind, Sandy primarily avoided the concept of attraction and relied almost entirely on repulsion to explain trends. When asked what caused attractive forces, she replied by stating what caused repulsion instead (See Table 4.3). When discussing how atoms at the bottom left corner of the periodic table have the largest radius, she stated, "There is more repulsion because it's making it farther apart from the nucleus."

The second major issue regarding attractive forces occurred when a student failed to recognize the effect of nuclear charge, caused by the protons, on the attraction of a single valence electron, rather than multiple electrons attracting the nucleus. The protons within the nucleus attract all of the electrons towards the middle of the atom, but multiple electrons would attract the nucleus in various directions and the effect would effectively cancel out. Macy illustrated this perspective when she was asked to identify what controlled the amount of attractive force. She responded by stating, “The number of electrons that there are.” This conception led Macy to give incorrect predictions for the atomic radius in a group, the anion radius, the second IE for potassium and calcium, and the electronegativity in a group. In each of these cases, she used the argument that a change in the number of electrons caused the attractive forces to change without ever referring to the number of protons present. For example, she incorrectly predicted the change in the radius when fluorine gains an electron, stating:

Because when you add an electron it gets closer to the nucleus because
the nucleus has protons in it and opposite forces attract.

It can be seen from this example that understanding the attraction of protons for electrons is not sufficient. There must be a focus on the number of protons and the role they play in attracting any single valence electron. This can then be balanced by the repulsion from other (primarily core) electrons.

Like Macy, Monica also recognized the importance of attractive forces and knew that electrons are attracted to the nucleus although she could not specify whether the protons or neutrons were the cause of the attraction. Perhaps, due to this uncertainty

regarding the source of the attraction, Monica stressed the role that distance played in controlling the amount of nuclear attraction. When asked to describe the attractive forces within an atom, she stated:

Attractive forces are when the closest orbitals have electrons that fill the shells allowing a stronger attraction.

Her understanding of the importance of the distance of valence electrons from the nucleus (controlled by the principle energy level) helped her with group trends and she was able to give a reasonable explanation for the atomic radius and ionization energy in a group, but her lack of clarity on nuclear attraction made it difficult to explain other types of trends. This was illustrated when she incorrectly predicted that the second IE for magnesium would remain unchanged. She explained this by stating:

I think the same possibly because they're in the same shell so they're like the same distance away from the nucleus and maybe they can possibly have the same amount of energy needed to take them [electrons] away.

Monica understood attraction to be controlled primarily by energy level. Since the energy level remained unchanged for both electrons, she predicted that the IE would also remain unchanged.

Issues regarding single/paired electrons. Increased repulsion occurs whenever two electrons are paired up within a single orbital since both electrons have the same charge. While not every student correctly understood the significance of paired electrons, most students had some concept that paired and single electrons behaved differently. The

most unproductive conceptions involved the idea that paired electrons either attracted each other, or that the atom wanted its electrons to be paired. This was expressed in an extreme form by Sonya, who had many correct conceptions concerning force, but felt that paired electrons in an orbital formed a bond. She stated:

In single electron . . . it would need another electron with it to bond with it to make it stronger to make it stable. When there's only one electron in a box [orbital] it means that it's more unstable so it's easier to pull apart.

The idea that two electrons paired in an orbital actually form a bond suggests that she had made a connection between paired electrons in an atomic orbital and paired electrons in a covalent bond. She missed the idea that even in a covalent bond, the electrons are not attracted to each other, but instead are attracted to the nuclei of the two atoms. It is because the attractive forces between the bonding electrons and the two nuclei are greater than the repulsion felt between the two electrons in the orbital that a bond forms. Sonya used her ideas concerning bonded electron pairs when attempting to explain the IE exception from nitrogen to oxygen. She got off to a difficult start by choosing to use Bohr drawings rather than orbital diagrams, and positioning the electrons of each shell in groups of two as seen in Figure 4.4.



Figure 4.4. Sonya's representation of the nitrogen and oxygen atom after losing an electron.

She reasoned as follows:

In nitrogen, the electrons would be bonded with each other and in oxygen, it would have one that's not bonded with another electron which would make this [oxygen] more unstable which would make it easier for it to take away an electron than it would for to take away an electron from nitrogen.

She appeared to forget that in her drawing, the electron has already been taken away when she said that it would be easier for oxygen to lose the un-bonded electron.

Like Sonya, Sandy also had the understanding that paired electrons had increased stability and unpaired electrons experienced increased repulsion (See Table 4.3). She used this reasoning to explain the radius of cations, anions and the exception in IE from beryllium to boron. When explaining why boron has a smaller first IE than beryllium, she said:

Taking away an electron [from boron] will create less repulsion between the other orbitals, so it's able to stay. You want to pair the orbitals, so making them paired will make it more neutral, like the ionization level would be more.

Rhonda's entire conception regarding the forces within an atom revolved around the pairing of electrons in orbitals. She stated, "Paired electrons cause repulsive forces. Single electrons cause attractive forces." While paired electrons do repel each other, the role of protons in attracting electrons is totally missing in Rhonda's explanation, and in its place is the incorrect idea that single electrons attract other electrons to the orbital, in a manner very reminiscent of Sonya's conception of bonded electrons. It is clear from the inconsistency of Rhonda's explanation, that she does not understand how electrostatic forces function. While Rhonda defined forces as being controlled by the pairing of electrons, she never used this idea to explain any trend but instead relied on her understanding of shells in most explanations. It is possible that her conception of forces was too confused and contradictory to be of much practical value as she tried to make sense of the periodic trends.

Issues regarding conservation of force misconception. The last force related issue experienced by students was misconceptions related to conservation of force. This issue was not included in the DSK assessment. It was unique in that it was only manifested during the explanations that students gave for two of the periodic trends: ionic radius, and second ionization energy and was coded as the additivity heuristic. It was also unique in that four of the five students who had this misconception, and used the heuristic

were classified as having adequate DSK about forces. Sonya, the one student using this heuristic who was classified as having inadequate DSK in forces, could discuss both attraction and repulsion acceptably except when discussing paired electrons. It is probable that the use of the conservation of force conception was only possible if the student had a basic understanding of attractive forces to begin with. In order to conceive of the idea that the attractive force will increase when there are more protons than electrons, the student needs to understand that protons and electrons attract each other, but that the focus is on the attraction of the protons for the electrons.

Summary of forces. Those students classified as having an inadequate understanding of forces demonstrated a variety of ideas that differed from those that are scientifically accepted. Those students who experienced difficulty with repulsion, generally saw it as the absence of attraction. Other students failed to see the central role of protons in determining the amount of attractive force. Several students thought that paired electrons experienced attraction for each other making them more stable. Each of these ideas contributed to incorrect predictions or inadequate explanations for periodic trends. The one misconception that was almost exclusively held by those students with an adequate understanding of forces, was the conservation of force idea that the nuclear force is shared equally by all valence electrons. Rather than contributing to incorrect predictions, this misconception helped the student to correctly predict trends, thus reinforcing the idea.

Of the six students categorized as having inadequate DSK in the domain of forces, only one student regularly used both attraction and repulsion to explain trends. The five remaining students either avoided forces altogether or used only one of the two concepts. This is summarized in Table 4.4. It seems clear from this data that inadequate DSK in the domain of forces often results in incomplete explanations of periodic trends. All of the periodic trends studied are caused by the combination of attractive and repulsive forces. When a student did not have adequate DSK in the domain of forces, they would often choose to use only the force they felt most comfortable with, or would avoid forces completely as they formulated their explanations.

Table 4.4

Inadequate Force DSK: Use of Attraction/Repulsion in Periodic Trend Explanations

Student	Type of Force used*
Macy	Attraction
Monica	Attraction
Rhonda	Neither
Sandy	Repulsion
Sonya	Attraction, Repulsion
Tina	Neither

* Any force had to be used for a minimum on two trends to be listed.

Issues caused by an inadequate understanding of the ionization process. An understanding of the ionization process was important in predicting all of the trends other than those dealing solely with radius. For this reason, the students were not only

questioned about the ionization process, but were given instruction during the course of the interview if their understanding seemed inadequate, so that the rest of the problems could be posed to them productively.

Students were asked to represent the ionization process for sodium by writing a chemical equation and were also asked to define ionization energy. Five students (Macy, Monica, Rhonda, Sandy, and Tina) were assessed as having inadequate understanding. These students were the same ones that had inadequate understanding of forces, with the exception of one student (Sonya) who had trouble with forces, but appeared to understand ionization. All five students with inadequate understanding of the ionization process represented ionization with an incorrect chemical equation (see Table 4.5). In addition, four (Rhonda, Tina, Monica and Sandy) were also unable to provide a correct definition of ionization energy.

Table 4.5

Student Equations Representing the First Ionization Process and Their Definition of Ionization Energy.

	Equations and Definiton
Rhonda	$\text{Na}^+ + e^- \rightarrow \text{Na}^-$ <p>It has the greatest amount of energy required because its-orbital shells are almost all full.</p>
Macy	$\text{Na}^+ \longrightarrow \text{Na} + e^-$ <p>Ionization energy is the energy that is required to remove an electron from its ground state, so the first ionization energy would be the energy to remove the first electron from the atom.</p>
Tina	$\text{Na} + e^- \rightarrow \text{Na}^-$ <p>The energy needed to either add or take away one electron.</p>
Monica	$\text{Na} + e^- \rightarrow \text{Na}^-$ <p>The first ionization energy is the first set of electrons on the first orbital. They have the greatest repulsion because they are closest to the nucleus.</p>
Sandy	$\text{H} + e^+ \rightarrow \text{H}^+$ <p>The full core electrons are filled and the ionization is at the highest in the upper right corner such as Fluorine.</p>

Of the equations shown in Table 4.5, only the equations written by Tina and Monica showed conservation of charge. Sandy showed confusion about the charge of the electron (which seemed to have been a one-time event). Both Rhonda and Macy started with a positive ion rather than a neutral atom. Four of the five students showed an electron being gained rather than lost. Tina's definition did capture the idea that an

electron was being transferred even though she was unsure whether it was gained or lost. The remaining students discussed the conditions needed for IE to be high with Rhonda and Sandy giving full shells as the criteria and Monica citing distance.

The lack of clarity expressed by these students concerning the ionization process and the definition of the first IE had the potential to make it very difficult to explain trends in IE even after being provided with a short review of the ionization process. Those students who demonstrated the highest level of confusion on their definition of first IE, Rhonda and Sandy, demonstrated an inability to provide an explanation for the first ionization trend. For example, when explaining the first IE down a group, Sandy stated:

As we go down a group, it's going to be higher up here because there's less protons and neutrons and electrons. Because having less of them makes the ionization higher. . . . Ionization, the point is to take away electron, not to gain it. So as we go down the group, we're gaining them and at the top what the ionization wants to reach is the smaller electrons.

Like Sandy, Rhonda relied on the number of electrons to explain the first IE trend, stating:

Because there's an increasing amount of electrons as you go down, so then you have to take more energy to take away an electron. It is getting bigger. . . . Since it's getting bigger, the electrons are farther away from the nucleus, so it takes more energy.

While there is no way to differentiate the influence of inadequate DSK in the two domains of force and the ionization process on individual explanations, it seems probable that both contributed to the difficulties that students experienced.

Impact of Inadequate DSK on Frequency of Heuristic Use. In order to determine whether there was any difference in the type of reasoning used by the students exhibiting an inadequate DSK in at least one of the three domains and the students exhibiting adequate DSK in all domains, the individual heuristic codes used by each group was tabulated to find the total code responses per student and then graphed as shown in Figure 4.5.

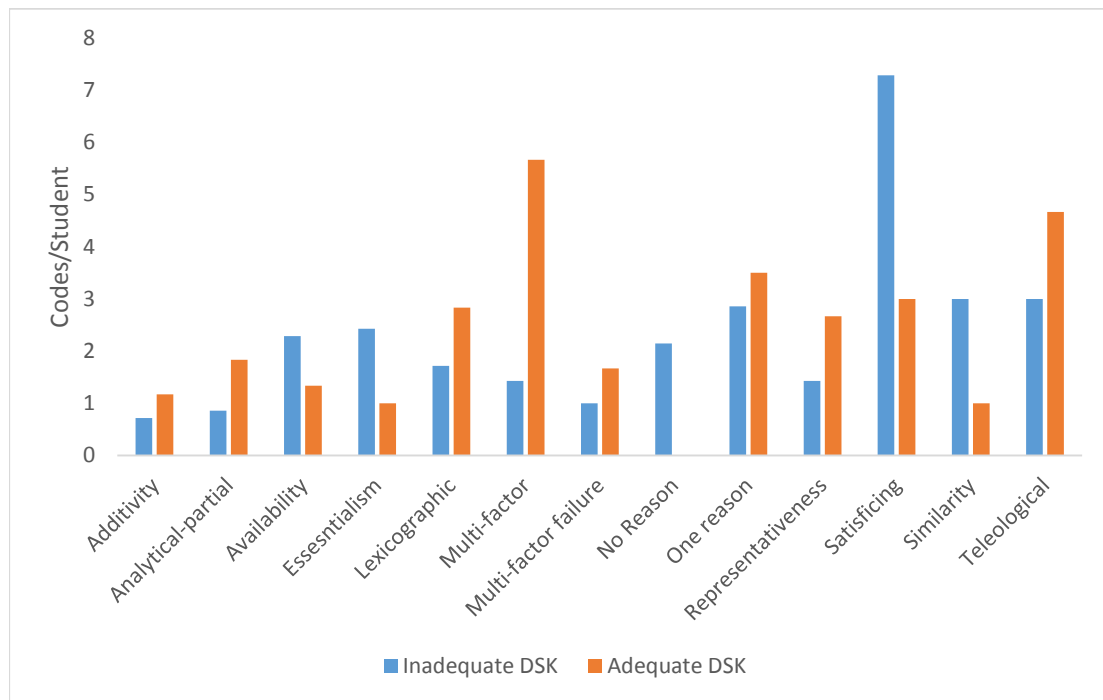


Figure 4.5. Comparison of reasoning strategies used by students with adequate and inadequate DSK.

The largest difference in the type of reasoning used by the two groups was that the group with inadequate DSK used satisficing and no reason strategies much more

frequently than those with adequate DSK, while those with adequate DSK used multi-factor reasoning with higher frequency. The next few sections will highlight each of the codes that showed significant differences in the frequency of use by students with adequate and inadequate DSK.

Multi-factor reasoning. Student responses were considered to be multi-factor if they included at least two factors, showed how together they influenced the specific outcome without ignoring a factor that would counterbalance one of the factors they chose to use in their explanation. Of the 35 multi-factor coded responses, 29 were from the six students showing adequate DSK in all three domains (4.8 codes/student), while six coded responses were from the seven students with inadequate DSK in at least one domain (.9 codes/student).

After observing that a significant number of students with inadequate DSK were still using multi-factor codes, the content of the factors used was further analyzed. Two distinct types of multi-factor reasoning were observed: (i) Multi-factor reasoning that included teleological arguments and (ii) multi-factor reasoning that relied on causal/mechanical type reasoning. Thus each argument that had previously been coded as multi-factor was sub-divided into two new codes: multi-factor scientific reasoning and multi-factor blended reasoning. The multi-factor scientific reasoning included no teleological component and the multi-factor blended argument included both teleological and causal/mechanical reasoning. 24 of the 35 multi-factor codes were classified as multi-factor scientific and 11 were coded as multi-factor blended. Figure 4.6 shows the

breakdown of the two types of multi-factor strategies for those students showing adequate DSK in all areas, and those that had at least one area of inadequate DSK.

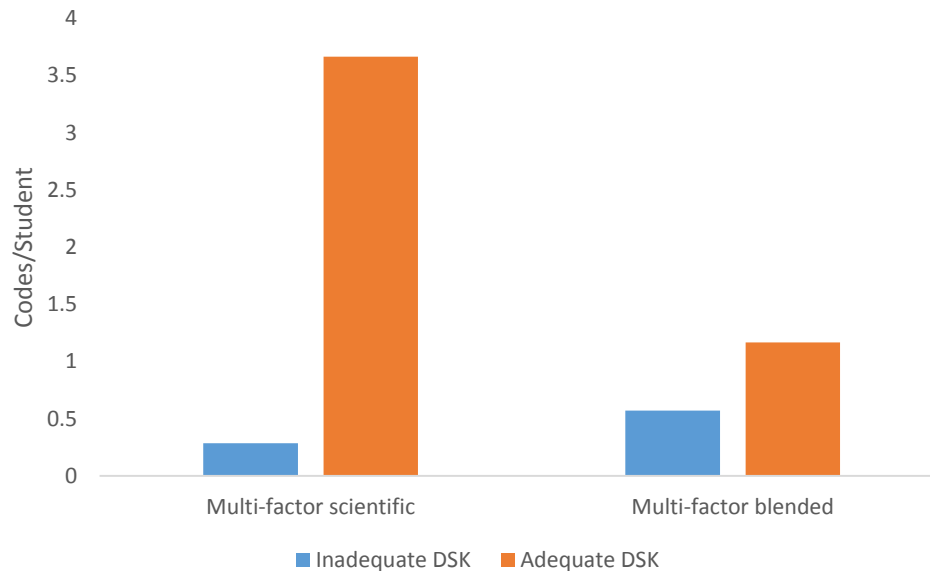


Figure 4.6. Multi-factor scientific and blended responses.

Once again, a marked difference in the reasoning demonstrated by those students with adequate DSK and those with inadequate DSK can be seen. While the students with adequate DSK used both scientific and blended multi-factor reasoning, they used multi-factor scientific reasoning to a much greater extent, with a total of 22 responses, while they used multi-factor blended in only seven responses. Those students with inadequate understanding used less multi-factor reasoning of any kind, but when they did, it was more likely to be multi-factor blended rather than scientific reasoning (four blended versus two scientific responses).

Multi-factor scientific reasoning. Six of the seven students classified as having adequate DSK utilized multi-factor scientific reasoning at least once. Nathan, a student

classified as having adequate DSK used multi-factor scientific reasoning for six of the fourteen trends. For example, when explaining the atomic radius trend in a group, he stated:

I know that potassium would have a whole extra ring, or an extra orbital than sodium, magnesium or sulfur, as the outer shell on those would be the 3s or the three orbital, and this one would have the four. So that [4s-orbital] would be further away from the nucleus. . . . Also, the core electrons, there would be more of them, more core electrons in potassium than any of those others in the third period. . . . [The core electrons] they're repulsive . . . so they would repel the outer electrons in a way that would make them go further from the nucleus. . . . There's more protons as you do go down the table which would draw, would be more attractive forces, but I believe that because they get further out, that it kind of overcomes I guess. . . . Overall, I would say that basically potassium has the greatest atomic radius because it is furthest away, its outer electrons are furthest away from the nucleus, being in the 4s-orbital in comparison to the three orbitals. And also that there would be more core electrons in potassium that would cause more repulsion of the forces making them bigger, making the atom bigger.

Nathan used the three most relevant factors, explained how each factor affects the radius and decided that the orbitals are the most important. He saw that increasing protons has the opposite effect of increasing core electrons, but did not make the connection that the

combination of increasing protons along with increasing core electrons give an effective nuclear charge that is almost the same as you go down. He had difficulty reconciling the opposing factors of attraction and repulsion, but still used more sophisticated reasoning than many of the other students, demonstrating his understanding of atomic structure and forces.

Of the two multi-factor scientific reasoning responses coded for those with inadequate DSK, both instances were attributable to Sonya, who only showed deficiencies in the domain of forces. Even in the area of forces, however, her understanding exceeded other students who were classified as inadequate, many of whom had a hard time articulating the basics of attraction and repulsion, which Sonya could do. An example where Sonya demonstrated a low level of multi-factor scientific reasoning occurred when she discussed the radius of the sodium ion after losing an electron. She stated:

The size will become, the radius will actually become smaller because there are more protons and there are less electrons to repel each other. And since there are more protons, there's more pull to bring electrons closer. . . . Well not more protons, but there's less electrons to be attracted to the protons, so that means that the proton is able to pull more. . . . So sodium . . . it would go up an energy level which would cause it to have a small radius because you'd have less rings.

While Sonya's reasoning was classified as multi-factor scientific because it utilized the scientific concepts of attraction, repulsion, and energy levels, it was not without scientific error. She demonstrated an additivity mindset, by expressing the idea that proton

attraction is a set amount based on the number of protons and is equally distributed among valence electrons.

Multi-factor blended reasoning. Multifactor blended reasoning was used by students with both adequate and inadequate DSK as seen in Figure 4.6. Seven multi-factor blended codes were assigned to students with adequate DSK and four blended codes were assigned to students with inadequate DSK. For students with adequate DSK, this represented a drop from the 22 multi-factor scientific codes assigned while it was an increase for the students with inadequate DSK who had only two scientific codes assigned.

Some students who were classified as having adequate DSK, used multi-factor reasoning, but still gravitated towards the blended argument. Katie was one of those students. While her DSK was adequate, she seemed more committed to teleological reasoning than reasoning based on forces. For example, when explaining the trend for the ionization energy across a period she stated:

As you go from left to right it [IE] gets higher because like let's say you had a noble gas and you're trying to take away one electron, it's not going to want to lose that electron because it will have a full valence shell, but then if you have an alkali metal, then they do want to lose that extra electron because if they lose that electron, they will then become the next noble gas in the next row. . . . The farther right you go, the higher the proton count is. So then the stronger the pull will be

between the protons and the electrons so it will be less likely to give away a valence electron compared to one with less electrons.

The most important argument for Katie was the atoms desire to have a full shell of electrons like a noble gas. Only after probing for additional thoughts did she use an argument based on attractive forces. While the attractive force from the protons is a scientifically based argument, Katie does not mention repulsion (which does not increase as much as attraction since core electrons are unchanged), and relies heavily on the non-scientific teleological argument.

Macy, who displayed inadequate DSK in all three domains, was coded as multi-factor blended for only one trend, the explanation of the second IE of potassium. Macy began her explanation by stating that the second electron that potassium lost would come from a different energy level than the first electron which was lost, “You’d have to go to this level.” When asked how the change in level would affect the energy needed, she stated:

Harder, because it’s [a] more stable shell. There are six [electrons] in there. It’s easier to take off this one [the electron in the higher energy level] because there’s just one. . . . This is the furthest from the nucleus so it’s easy to take it away. It’s going to be harder to take this one away because it’s closer to the nucleus.

Like Katie, Macy uses the stable full shells argument (6 electrons in the p-orbital fill up the second level) which is a teleological argument. Macy then blends the teleological argument with a distance-based explanation which is a scientifically more appropriate

argument because it implies that the forces are stronger between the electrons and the nucleus. Even her distance argument however did not explicitly make reference to forces of attraction and only that it was ‘harder’ for the second electron to leave because it is closer.

Based on the distribution of all instances of multi-factor reasoning, as well as the sub-category of multi-factor scientific reasoning, it would appear that those students with adequate DSK have increased ability and willingness to work with multiple factors while solving problems in general, but specifically they are better able to produce scientifically credible arguments due to their more sophisticated DSK. This does not necessarily mean that those students with inadequate DSK cannot work with multiple factors to solve problems. Four of the six students classified as having inadequate DSK were able to use multiple-factor reasoning in some form for at least one of their responses, drawing on the octet rule along with force related ideas from the course. This indicates that multi-factor reasoning is enhanced by a higher level of DSK, but most students are capable of using more sophisticated reasoning and will do so on occasion. It may also demonstrate how difficult it is to dislodge previously learned less scientifically based ideas, even after new ideas are accepted. Rather than dismissing the previously held ideas, many students learned to blend them with the newer, more scientifically appropriate concepts.

Satisficing and fixation. At the opposite end of the spectrum from multi-factor reasoning, are the heuristics of satisficing and fixation. Satisficing occurred when a student was satisfied to use one primary factor that did not adequately explain the periodic trend while ignoring other factors that either opposed the conclusion decided

upon, or that were essential to explain the trend. Fixation is the mindset that led a student to use the same explanation, centered around a particular factor for multiple problems, even when the nature of the problem changed, and to ignore other factors that might give a more effective explanation (Furió et al., 2000; Talanquer, 2006). When a student displayed fixation with a particular factor or explanation, they tended to overgeneralize the principles which worked well in one situation, to other quite dissimilar situations.

While almost every student used satisficing, the seven students with inadequate DSK used it 43 times while the six students with adequate DSK used it only 13 times. Of the 13 satisficing references made by students with adequate DSK, eight were made by one student, Corban, while the other students used it a maximum of two times. Table 4.6 shows that when students used satisficing, they tended to rely on the same concepts to explain multiple problems. This tendency was coded as fixation if the students' reasoning strategies followed a similar pattern based on one or two related factors in at least seven of the 14 possible problems situations that they encountered in the interview. As seen in Table 4.6, the only student with inadequate DSK not coded with fixation was Sonya. The only student with adequate DSK who was coded as using fixation was Corban who also was coded with eight satisficing responses.

Table 4.6

Comparison of Students' Use of Satisficing and Fixation as Reasoning Strategies

Student	Adequate (A) or inadequate (I) DSK	Number of satisficing responses	Fixation Mindset (Fixation factor)
Macy	I	8	Number of electrons
Monica	I	3	Number of shells
Rhonda	I	8	Number of shells
Ronald	I	5	Proton attraction
Sandy	I	7	Electrons
Sonya	I	6	NA
Tina	I	7	Orbitals/shells
Corban	A	8	Orbitals/shells
Loni	A	2	NA
Krissy	A	1	NA
Nathan	A	1	NA
Katie	A	1	NA
Karla	A	0	NA

Rhonda is an example of a student with inadequate DSK in the areas of force and ionization, who depended on satisficing and had a fixation for utilizing the number of electrons/orbitals for the majority of her reasoning. Table 4.7 gives some excerpts from her interview to illustrate her reasoning for several trends.

Table 4.7

Rhonda's Use of Fixation

Periodic Trend	Excerpt from interview illustrating reasoning
Atomic radius - Group	Sodium was the smaller one because it is higher on the periodic table. . . . It has less electrons. . . .Something about its shell. . . . Isn't it a lot smaller, it's all like they're closer to the nucleus?
Atomic radius - Period	The electrons are moving farther away from the nucleus, there's becoming more of them. . . . Because there starts to form more shells and so then the electrons are getting farther away from the nucleus.
Anion radius	I think it [radius] would stay the same because we're just filling the shell, you're not adding on a completely new shell.
First ionization energy - Period	Oh, I think you would also increase because as you're moving it's moving farther, it's going farther away from like the different like the shells are still getting bigger as you move across the period. I think that since it is still getting bigger, it would still be harder to take one away.
First ionization energy - Group	Oh because there's like an increasing amount of electrons as you go down, so then you have to take more energy to take away an electron. It is getting bigger.
Electronegativity - Group	As you go down, it increases in electrons. So I think that would make it more. The more electrons the greater the electronegativity.

As Table 4.7 illustrates, almost all of Rhonda's reasoning revolves around the number of electrons which translates into either an increase or decrease in the number of shells. While the number of shells is the most important factor when explaining the atomic radius in a group (where it was coded as one-reason), it was no longer a factor in the period. Similarly, when Rhonda tried to explain the IE in a group, she used the same reasoning that she used for the atomic radius when she said that the increase in electrons

and atomic size caused the IE to also increase – an incorrect prediction. She did not explain why the increase in atomic radius would have an effect, but simply stated it as a given.

Rhonda utilized both satisficing and fixation, by focusing on a very limited set of factors. She satisficed by using the factors inappropriately and without sufficient justification in most cases. She demonstrated fixation by confining her explanations primarily to the number of electrons and shells. Because Rhonda did not have adequate understanding in the domain of atomic forces or IE, she necessarily limited her explanations to atomic structure. Even her understanding of atomic structure was limited by her failure to fully appreciate the differences between shells and subshells. Her inadequate DSK in the domain of atomic forces placed a severe limitation on the type of factors that could be used and helps to explain why the terms ‘force’, and ‘repulsion’ are entirely absent from her explanations and the term ‘attraction’ is used only once.

Like Rhonda, several other students with inadequate DSK - Macy, Sandy and Tina, showed a tendency to use the satisficing heuristic and were also coded as utilizing fixation with either electrons or orbitals/shells. Monica also demonstrated a fixation with orbitals and shells, but her reasoning was a spread between satisficing, one-reason, and no reason given. The widespread use of satisficing and fixation by students with inadequate DSK is an indication of the limitations imposed when conceptual understanding is low. These students all showed inadequate understanding of forces and the ionization process. Two of the five students used an explanation utilizing forces only one time, and the others could only discuss one of the two types of forces (see Table 4.4).

Most of these students were more proficient in the atomic structure domain. They were aware of how many electrons were present and had a general understanding concerning which shells the electrons occupied. They used their understanding of electrons and shells to construct explanations even though these factors were not usually sufficient or used in a manner that justified the conclusion that was proposed.

No-reason/memorization. The ‘no reason/memorization’ code was used for any student that responded with a prediction for a periodic trend but did not give any reasoning as to why the trend occurred other than that they had memorized it, or if the trend was given to them, they did not attempt an explanation. There were 15 responses coded by students with inadequate DSK as no reason/memorization or 2.14 responses per student, whereas none of the students with adequate DSK were coded in this way. It was interesting that many of the students with inadequate DSK relied on memorization even though they had been told that they would be expected to explain their reasoning on the exam.

Sandy and Tina had the highest frequency for responding that they could not explain a trend, with each being coded as ‘no reason/memorization’ for three different trends. Sandy correctly predicted every trend for which a prediction was required because she had memorized them in high school, which was sufficient to earn a good grade. When describing her high school chemistry unit on periodic trends, she stated:

It was like I was best at it in my class, of the periodic trends and stuff. I don’t know, I just understood it. . . . Basically he would give us a periodic table and you’d say in the right-hand corner is the highest

ionization level. In the left-hand corner is the biggest radius. . . . I think that's just how I pictured it from high school.

She seemed to equate memorization of the trend with understanding when she describes how she understood it and was able to tell which corner of the periodic table had the highest ionization energy in high school. When asked about the electronegativity in a group, a trend not discussed in the current class, she stated without hesitation:

Going down a group it would be, electronegativity would be less. . . . I know it has to probably be something about orbitals, but I don't know. Our trend in high school.

She made similar statements concerning two other trends. She did not seem inclined to prioritize explanations which went beyond what had been required to succeed in her secondary coursework.

Tina also tried to rely on memorization, but was not as successful. She declined to give an explanation for three of the first seven trends which were those that had been discussed most extensively in the course. An example of her overreliance on memory occurred when she was asked for an explanation for the trend in first IE in a period.

I think the ionization energy gets smaller the more you move towards the right. It's like biggest over here and it gets smaller. The biggest one is this bottom corner, the bottom left. . . . I just memorized it like, I had a thing with the different arrows. Like the atomic radius, the ionization energy, like that kind of stuff with arrows and I just tried to memorize that.

Tina had successfully completed two chemistry courses in high school, one of which she described as advanced chemistry that was designed to cover the topics from a first semester college course. Yet with all this chemistry experience, she still did not seem to understand the necessity to go beyond the memorization of arrows that pointed to where the trend increased in value.

Memorization was probably important to all of the students as they studied periodic trends. It may have served as a guide when they tried to explain the reasons behind each trend. Those students with inadequate DSK seemed to substitute memorization for conceptual understanding to a greater extent. Perhaps they were conditioned by previous classes to feel that when a fact was memorized, it was also understood. It may also be the case that those students with less interest in science did not have the motivation or curiosity that is necessary to go beyond memorization to understanding.

Outlier sample analysis. In the previous section, the relationship of a student's DSK and their reasoning strategies was discussed. Some general patterns emerged about how students with adequate and inadequate DSK differ in their heuristic use. However, there was one student, Corban, classified as having adequate DSK that seemed to respond with a pattern of reasoning that was closer to that of the students with inadequate DSK. Unlike other students with adequate DSK, Corban was never coded as using multi-factor reasoning. Instead, he had the highest number of teleological codes, was tied for the most satisficing codes, and was coded as having a fixation with the full shells teleological

argument. This section will explore this deviation from the general pattern of thinking and attempt to find some reasons why it may have occurred.

The fundamental difference between Corban's reasoning and the other students classified as having adequate DSK was his lack of multi-factor reasoning. Rather than utilizing all of the concepts that he had learned, Corban often settled on incomplete explanations that depended on a fixation with the idea that atoms want shells that are completely filled with electrons – the full shells, teleological argument. He had difficulty combining the concepts he understood in an interactive way that showed their relationships to each other. When he attempted to combine reasons, he often ended in confusion and came back to his filled shells argument. An example of Corban attempting to use multi-factor reasoning, but falling short, occurred when he discussed the trend for the IE across a period. He explained:

So there is going to be one valence electron [in sodium], and in sulfur there's going to be six. So even though there's more repulsion going on, the amount of protons in the nucleus is going to want to . . . attract the electrons. Like if you have a bigger nucleus and it keeps expanding and even though the atomic radius is going to be large [pause] no, the atomic radius as you go down and left is going to be larger, but if you have [pause] these will have three orbitals and this will also have three orbitals according to this. This [sulfur] will have six [valence electrons], so it will be mostly filled. It's going to take more energy and then just the one valence electron to take away. If it has a more filled

shell it's going to take more energy to take it away rather than just one valence electron.

In this explanation, Corban mentions repulsion, attraction and orbitals (meaning energy levels), but he does not explain why the proton attraction is more important than the electron repulsion or why the number of orbitals matter. He seemed to be having trouble putting it all together so he goes back to his teleological filled shells argument. This explanation was coded as lexicographic because while he brought up both attraction and repulsion, he seemed to abandon both ideas in favor of the full shell argument, which he found easier to articulate.

Like the students with inadequate DSK, Corban used satisficing as his primary reasoning strategy. An example of how he used satisficing can be seen in his explanation of the reactivity trend in a group. He stated:

In my mind, the more electrons and protons that you have, and I guess, not protons just electrons, in general, in an atom the more vigorous [the reaction]. I can't say that, I guess if you go to the right because this has more electrons, iron rather than potassium, but I feel like if you have one valence electron in the outermost shell, I feel like [it is] more vigorous. I guess it only goes just per group, but per group if you have more electrons but you still have one valence electron, it's going to be more vigorous.

Corban distilled the reason for increased reactivity down to one reason; the number of electrons. He recognized that this reasoning contradicted the reactivity trend in a period,

but rather than coming up with alternative reasoning, he simply qualifies the reason as only being valid in a group. Unlike the students with inadequate DSK however, Corban had an understanding of all of the critical concepts needed to give complete explanations for the periodic trends. He not only understood the basic causes of attraction and repulsion, but he knew that the protons determined the amount of attraction felt. He could identify core electrons and discussed the repulsion they experienced with the valence electrons. This concept knowledge did have an effect on his reasoning. His reasoning differed from the students with inadequate DSK in that he used a larger variety of factors during the course of the entire interview. He used both attraction and repulsion in his explanations rather than exclusively one or the other. He also used the repulsion caused by electron pairing and core electrons, and mentioned energy levels although he often minimized their effect. None of the students with inadequate content knowledge used the wide variety of factors that Corban was able to utilize.

There is no simple explanation for the differences that were seen between Corban and the other students with adequate DSK, but some clues did emerge that helped to give insight. Like Sandy, a student with inadequate DSK who depended heavily on her high school experience, Corban experienced a rigorous high school chemistry course that he referred to several times within the interview. When discussing his atomic picture of sodium, he stated:

Just personally, I just knew that from chemistry back in high school,
that each orbital [was] two dimensional. The first, inner [orbital] is

always going to have two [electrons] and then each one is going to want to be filled with eight. So that's what I learned.

As a result of his high school chemistry course, Corban learned some rules about the atom that he remained committed to even after the passage of several years. One of these rules was that atoms want to have full shells. He referred to this rule in the majority of his periodic trend explanations. A clear example of his adherence to this rule of thumb occurred as he was explaining the second IE for potassium. He stated:

I guess I'll go back to the fact that every single orbital wants to be filled to the maximum. . . . I guess the reasoning why, I couldn't tell you except for the fact that I just, that's what I always thought of it as. . . .

This shell just wants to be filled. I guess that's the only reason why.

This rule became the cornerstone of Corban's thinking about the periodic table, and while he added to it at times, no other rule or concept ever came close to achieving the same authority.

All of the students made an attempt to memorize the periodic trends that were discussed in the course. For many of the students with adequate DSK, their memorization of the trend and their understanding of the reasons behind it had merged into a coherent whole. The reasons made the trend meaningful to them. For Corban, this did not seem to be the case. He always attempted to supply an explanation for every trend, but it appeared that his memorization of the periodic trend was primary, while any reasons for it appeared to be secondary. He started his explanations for several periodic trends with phrases such as, "I remember in class...", or "As we learned in class..." When attempting

to come up with a reason for the exception to the IE trend from beryllium to boron, he stated:

I honestly couldn't tell you. In class when you told us there was a ton of exceptions, I was like shaking my head, and I was oh no. No way exceptions because you have to sit there and you have to memorize the exceptions.

Corban relied on his ability to memorize trends, and then attempted to construct a reason that would justify the trend he had memorized. It would appear from his pattern of explanations that the only reason that helped Corban to construct meaning was that all atoms needed full shells.

In summary, although Corban was able to discuss all of the individual concepts needed in order to explain the trends, he experienced difficulty in combining them to create a more complete explanation. He was too easily satisfied with simple explanations that did not adequately take into account inconsistencies with previous explanations, or factors that might oppose the reasoning already initiated. This suggests that he was beginning to understand the implications of each factor, but was still experiencing difficulty when he tried to combine them. When combining factors, he started to experience confusion, which made it easier to use the full shell rule that he was more comfortable with. It is possible that because his previous success with the periodic trends in high school depended primarily on a combination of memorization and full shells reasoning, he was less inclined to spend time trying to understand the implications of the new concepts that he was learning.

Concluding statements about DSK. In this section, the relationship of student's DSK and their reasoning strategies was explored. It was found that only a few students experienced difficulty with atomic structure, and the effect on their reasoning appeared to be minimal. Almost half of the students experienced difficulty with the forces within an atom and most of this same group of students also had difficulty with the ionization process. While it was clear that a lack of understanding in both of these areas had an effect on student reasoning, it was not possible to completely separate the individual effects as both played a role in a complete explanation for approximately half of the trends. The analysis did show that those students with an incomplete understanding of forces often avoided discussing forces at all, or only discussed one type of force (attractive or repulsive) in ways which were often scientifically unsound and which were always incomplete. Since every periodic trend is caused by a combination of forces, it would appear that understanding in the domain of forces had a major impact on the reasoning of the students in this study.

A comparison of the reasoning used by students with adequate and inadequate DSK showed that students with inadequate DSK were more likely to use satisficing and to show a fixation with the use of a single factor whether it was scientifically warranted or not. Their explanations frequently revolved around full shells or distance without a clear relationship to the forces involved. Even when multiple factors were mentioned, often there was a preference for a blend of scientific and teleological arguments with an avoidance of any factor that might oppose the prediction made. Students with inadequate DSK also showed an increased reliance on memorized trends, perhaps failing to attach

any importance to the necessity of developing a deeper understanding of the underlying causes.

Students who had adequate DSK were more likely to exhibit multi-factor scientific reasoning. Because they had developed mastery in all domains needed, they were able to consider multiple factors concerning the forces and relate them in a variety of contexts. Even this group of students sometimes showed a bias toward the use of teleological, full shells thinking, or added this type of reasoning to other factors resulting in multi-factor blended reasoning. This was especially true of one student whose pattern of reasoning more closely resembled that of the students with inadequate DSK. It was found that even though he had learned the concepts in each domain and always developed an explanation for each trend, he had a deeper commitment to the use of memorization and the full shells rule that he had learned in a previous chemistry course. His bias towards teleological thinking helped him in making correct predictions, but seemed to hinder the development of a more multi-factor reasoning approach.

Research Question 3: Unfamiliar Trends

The third research question to be investigated stated, “What effect will an unfamiliar periodic trend problem have on the reasoning strategies utilized by undergraduate general chemistry students?” In this study, the trends in reactivity were utilized to provide an unfamiliar problem. While reactivity is an ongoing topic in the chemistry curriculum, it was not a focus of the unit on periodic trends nor were trends in reactivity explicitly taught within the unit. Thus, in explaining reactivity, the students

were attempting to apply the concepts they had previously learned to a new context that went beyond what had been experienced during the normal coursework.

The problem situation that was presented to students included a description of the reactivity of three, period four metals (potassium, calcium, and iron) with water, followed by a description of the reactivity of three group one metals (lithium, sodium and potassium) with water. Resources that were provided included the periodic table (available for all of the questions), chemical equations representing the reactions that occurred, and a table that included the first through fourth ionization energies for all of the elements involved (see Appendix B). In order to give a scientifically appropriate explanation, the students needed to understand IE, know the significance of sequential ionization energies, be able to use a chemical equation to identify when an element is oxidized, and see that the IE represents the energy needed to oxidize the metal. All of these concepts should have been familiar to the students. This section will discuss the unique heuristics that were used primarily in explaining the reactivity trends, explore any connection between the previous explanations used by students for familiar trends and those used for the unfamiliar trend of reactivity, and determine if there were specific concepts related to reactivity that caused confusion for the students.

Heuristics used uniquely for an unfamiliar trend. In order to identify those heuristics that were used primarily when explaining an unfamiliar trend, a comparison was done of the heuristics used for atomic radius (a very familiar trend that forms the basis for other trends) and reactivity as shown in Figure 4.7. While the most frequently used heuristics across all trends, (see Figure 4.1) satisficing, teleological, multi-factor,

and one-reason, were still used to explain the reactivity trends, other heuristics assumed places of greater prominence. These heuristics included representativeness, essentialism, similarity, and availability.

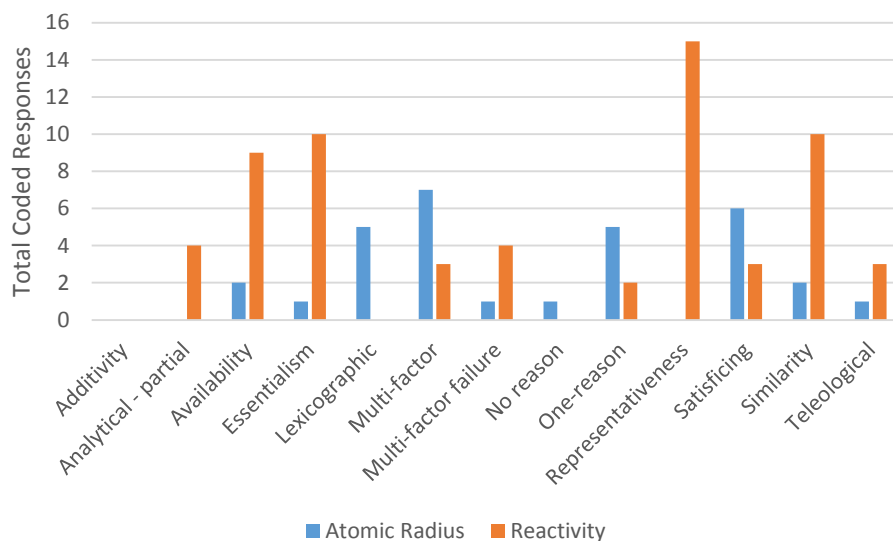


Figure 4.7. Comparison of heuristics used to explain atomic radius and reactivity

Representativeness Reasoning. The code assigned with the highest frequency to student reasoning in regard to the reactivity trend was the representativeness code which was used 15 times. This code was used when a student recognized that the reactivity problem was a part of the class of problems related to IE. This code was unique to reactivity, not necessarily because of the unfamiliarity of the problem, but because this was one of only two trends (reactivity and electronegativity) where the students could appropriately use it. Only one representativeness response was coded for the electronegativity trend, so for most students, the connection was either not made, or at least was not an important part of the reasoning process. The other trends that were presented to the students were either clearly identified as being about IE, or did not

involve the ionization process. The importance of representativeness reasoning is that it had the potential to act as a foundation upon which students could base the remainder of their explanation. In order to be successful in explaining reactivity, which was unfamiliar in this context, the students needed to connect it to a class of problems that was familiar. This recognition allowed the students to make connections to other factors that might be useful in explaining a problem of this type. Loni provides an example of a student recognizing that ionization energy was the key to the reactivity trend across a period when she stated:

Potassium has a single valence electron and so to me that would probably indicate why it reacts vigorously because that one can just be pulled away when it's reacting with water. And then the calcium has two valence electrons so pulling away the second electron would be harder but it can still be done but that's also I think why it reacts more slowly because it doesn't have like it's not as easy to pull away that first one because it's paired together and it's complete. Iron is in the middle of its . . . 3p-orbital and that one is more than half full That's a lower level than the 4s-orbital like the 3p, no 3d, excuse me, is a lower level than 4s and that is probably why it reacts poorly with water cold or hot because it's a lower level. Also it's just got more electrons in it.

While Loni never used the phrase 'ionization energy' she clearly uses it as the backbone of her explanation. She discusses the difficulty of removing electrons during the reaction,

the effect of removing multiple electrons, and the energy involved when removing an electron from a 3d orbital as opposed to a 4s. She did not give a complete discussion of all the factors that might be involved and did give evidence of some teleological thinking, but she still gave a reasonable explanation with IE as her focal point. She continued in the same vein when discussing the reactivity in a group, stating:

As you go down, the radius [of] the atom gets larger meaning that the valence electron is farther away than the protons and the closer it is the stronger the protons are going to have a hold with the electrons that it has. Like lithium it has a stronger pull on its outer electron and so it wants to keep that more than just let it go whereas potassium has multiple other levels and it can just go because it doesn't have as strong of a pull.

Here Loni uses the idea of attraction for the valence electron as a function of distance. Again, she does not specifically reference IE but she explains the primary factor, distance from the nucleus and its effect on the attractive forces holding the electrons, which result in the IE energy being lower at the bottom of the group, which leads to the higher reactivity of the metal. Loni is able to take the familiar trend in IE and apply it to the unfamiliar problem of reactivity. Only two other students, Katie and Karla were able to connect reactivity to the metal's ability to lose electrons and give reasons why some metals lose electrons more easily than others that were scientifically appropriate.

Other students were also coded as using representativeness reasoning because they connected IE to reactivity, but the connection was made due to the availability of the

IE chart provided and not due to any substantive understanding of its significance. This was the case for four of the students (Rhonda, Ronald, Sonya, and Tina). Tina's explanation was as follows:

I guess it has more to do with the ionization energies, the potassium has the lowest and so it would be, I guess, more likely to react with another thing versus iron is almost double that of a potassium so maybe it would just take something stronger to react with the iron versus the potassium because it doesn't need as much energy. Maybe the water just didn't create enough energy with it to actually cause a reaction.

Tina's explanation is very reasonable, but relies entirely on the chart's numbers. She never mentions electrons being lost, and does not give any explanation for why some metals have lower ionization energies than others which is consistent with her inability to explain the IE trend when asked about it in an earlier question. While she makes the connection to IE, this does not provide her with the resources to make further connections.

The other three students (Rhonda, Ronald, and Sonya) whose explanations depended on the IE chart, misinterpreted the information provided and came up with an explanation that was not scientifically appropriate. An example of this occurred with Rhonda's explanation of the reactivity in a period when she stated:

Like for potassium, it has a really high jump between ionization energies. . . . It takes a bigger ionization energy from first to second then for calcium or iron. I think that it would make it react more. . . .

It's gaining electrons because it is bonding with the oxygen and the hydrogen.

The other two students gave a similar explanation, referring to the large ionization energy jump as a reason for potassium's reactivity. With the help of the IE chart, they were able to connect reactivity to IE, but were not able to use this connection effectively. Rather than drawing upon other factors that could explain periodic trends, they looked at a surface characteristic from the chart that was unrelated to the increase in reactivity.

An additional two students (Corban and Krissy) also used representativeness reasoning. They did not refer in an obvious way to the IE chart that was available, but clearly connected the loss of electrons to increased reactivity for the reactivity trend across the period. Corban related the decrease in reactivity for iron to the increased number of electrons when he stated:

I guess iron, I think it has more valence electrons, it's going to want to react less vigorously because it's not going to give up its electrons as quickly as well as much as potassium or calcium do.

This is consistent with his full shells hypothesis that calcium and potassium will easily lose electrons to have a full outer shell, but iron has more outer electrons, and so would not lose electrons as easily. When he attempted to explain the trend for the group, he realized that more electrons do not result in less reactivity as it seemed to do across a period, so he revised his explanation to state, "Per group if you have more electrons, but you still have one valence electron, it's going to be more vigorous." He gave no

indication as to why this might be even though he had used electron repulsion to explain other group trends.

When confronted with the reactivity trend in a period, Krissy attempted to use several factors unsuccessfully and was eventually coded as using multi-factor failure reasoning, a code that was applied when a student considered several factors, but was either unable to combine the factors appropriately, or ended up without endorsing any of the factors considered. Krissy was coded as using multi-factor failure because she seemed to realize that her reasoning was not helping her to come to a conclusion. She stated:

So, size would get larger. I don't know if that makes it more reactive. It would be harder in their reaction to pull away an electron, because it would want to move away, maybe because [she paused, and then dropped that thought]. . . . So, maybe the higher the ionization energy, the more reactive it is, because it doesn't want to lose an electron. But I don't know how that would reflect it exactly.

Krissy connects reactivity to losing electrons and ionization energy, but her understanding concerning both seemed to depend on memorized facts that she was only beginning to be able to apply depending on the context. When working with only one concept in the ASSE or exam, she was able to give correct answers. When she was required to consider several concepts in order to make a decision, she ended up in confusion.

A review of the student responses using representativeness reasoning indicates that for the unfamiliar reactivity trend, representative reasoning was necessary for a

scientifically appropriate explanation, but was not sufficient. The connection of reactivity to IE helped the students to consider those factors that affected IE, but only if IE and its causes were understood to begin with. Those students that were able to capitalize most on the connection to IE (Karla, Katie, and Loni) were all students classified as having adequate DSK in all domains. Those students that used the IE chart inappropriately all showed inadequate DSK in at least one domain and three of the four (Rhonda, Sonya, and Tina) had inadequate DSK related to forces. In between these two groups were Corban and Krissy, who used representativeness thinking by connecting reactivity to the loss of electrons, but who still had trouble making appropriate connections to factors involving forces. Both were classified as having adequate DSK, but neither student pursued this connection in a scientifically productive manner. Corban may have been hindered by his reliance on memorization and the limitations imposed by his commitment to teleological reasoning. Krissy seemed to experience difficulty because her understanding of IE did not extend beyond the definition so that she could use it in an unfamiliar context.

Essentialism Reasoning. The remainder of the heuristics that were uniquely utilized for the unfamiliar trends included essentialism, similarity, and availability. Each of these heuristics represents a simplified rationale for the decision making process based on commonsense associations or presuppositions about the nature of the world (Talanquer, 2006). Essentialism is the empirical assumption that substances have an inherent essence or set of characteristics that are fundamental to their identity and require no further explanation. Many of the students started by using essentialism reasoning when asked about reactivity across a period. For example, Karla, a student that used

multi-factor reasoning to explain most trends, stated, “When you get more towards this side, the metal attributes, . . . I mean to the left, the metallic attributes kind of get stronger or more distinct?” Rhonda stated, “I think it depends on what the atom actually is. Because potassium was a different type of metal than iron. I think it would react differently.”

Eight students used essentialism to help explain reactivity across a period, the first of the reactivity problems presented. For four of the students, this was their first thought and when asked to explain further, they considered other factors. Three students used essentialism as their entire explanation and responded that they could think of no additional reasons for the change in reactivity. One student ended with essentialism when her initial explanation seemed unsatisfactory to her.

For some students, it appeared that when faced with an unfamiliar trend, their first response was a type of non-explanation, basically saying, ‘That is the way these metals behave.’ They did not immediately know the answer and were not sure how to connect the trend in reactivity with the other trends previously considered. The essentialism response gave them a way to answer the question and for some, it provided the processing time needed to consider other things. Even when essentialism was the only explanation given, as was the case for Karla, it seemed to provide her with processing space so that when she was asked about the reactivity in a group she was able to give a more complete, scientific response, stating:

When I think about the similarities, they have the same amount of valence electrons and also like the same position when it comes to the

last orbital or suborbital. . . . Maybe it's because the electrons, because the reaction is like electricity, like the electrons moving freely, so I think that as you move down the energy levels, the electrons are more likely to move because they don't have as much attraction as you move down the energy level. . . . The radius is getting bigger, because, when the effective nuclear charge is staying the same and then the energy levels are getting bigger. . . . When the radius is bigger, the protons don't have as much attraction over the electrons, especially the valence electrons.

While essentialism reasoning was important for students attempting to explain reactivity across a period, it played a minor role for the reactivity in a group. When comparing elements in a group, several students noted that the characteristics of the metals were the same. This had the effect that essentialism reasoning was no longer helpful in explaining any differences among the elements in the group.

Similarity reasoning. Similarity reasoning was the second type of commonsense association used primarily for the unfamiliar reactivity trend. Similarity reasoning was utilized for both periods and groups and was coded when a student assumed that an adjective that described the trend itself, such as large, would also be true for the cause of

the trend without applying scientific justification for the relationship. Table 4.8 illustrates some of the ways that similarity reasoning was used to explain the reactivity trend.

Table 4.8

Examples of Similarity Reasoning Used to Explain Reactivity

Student	Period/Group	Interview excerpt
Corban	Group	The more electrons you have per group, I guess the more vigorous the reaction is going to be.
Krissy	Group	So if we're going down, you're increasing an energy level, which means that if there's more energy, there's more heat. So it reacts to create more heat if there's more energy to react with.
Macy	Group	I know it has more electrons . . . more electrons then they're more negative. . . . Because the more negative of something the more it's going to react.
Rhonda	Group	Because it [potassium] has the most, the most electrons out of the three. So then the ionization energy like with taking electrons away. It has to like work harder so it's giving off more reaction. So it's working hard and that working harder produces more energy.
Ronald	Period	It has to do with the ionization energy because I noticed that these ones jump up at a relatively short jump, but when you look at potassium, it jumps from 419 to 3042 then another thousand jump. . . . Intensity [of reactivity] probably comes a lot from how much energy is actually required to pull away that first electron.
Sonya	Period	It took a lot of energy for this reaction to happen which in turn caused the water to become really hot as a lot of work was being done.

Some of the factors used by those students appropriating the similarity strategy included the number of electrons, the energy level, and the difference between successive IEs. These students used a surface characteristic that they could identify as increasing in the same way (right to left in a period, or down a group) in which the reactivity increased.

In some cases, the characteristic used (increasing energy levels) could explain the reactivity, but only when the student explained the dependence of nuclear attraction on the increased distance between the valence electrons and the nucleus when the electrons were in higher energy levels.

Availability Reasoning. Availability reasoning was the last type of reasoning utilizing commonsense associations that was used for the reactivity trend. Availability was coded when the student considered a factor because of its availability, or because it was recently used or very familiar to the student. The availability heuristic was used a total of 16 times in the study, with nine of the responses coded for the reactivity trend. The high use of availability by students for the reactivity trend was due in large measure to the availability of the IE chart for this question, which gave successive IEs for the elements reacting. Several examples of student responses for the reactivity trend, which were coded as availability, were discussed in the section dealing with the first research question. While not all students depended on the chart when explaining the reactivity trend, it was clear that a number of students did. If they used the chart inappropriately or without further explanation, they were coded as using availability in conjunction with other codes such as representativeness. When faced with an unfamiliar problem, it is appropriate to make use of all resources available. The resources were of limited value however when the students did not understand the underlying ionization process. The most common inappropriate use of the chart was illustrated by those students who felt that the gap between the first and second IE of potassium was the primary reason for its high reactivity as discussed in the section on representativeness reasoning.

Summary of Student Reasoning Strategies Used for Unfamiliar Trend. When faced with an unfamiliar trend, students used heuristics based on commonsense associations or presuppositions with higher frequency than were used on the more familiar trends. The commonsense heuristics used to explain reactivity included essentialism, similarity and availability. Essentialism was sometimes used as the only reasoning strategy, but was often used to provide a processing space for the student as they continued to think about possible causes. The similarity heuristic provided the student with a simple association between a structural feature such as the number or electrons or energy levels and the reactivity demonstrated by the element. While these associations could be useful if the student considered the forces underlying the association, the assignment of the similarity code meant that a consideration of forces did not occur.

The availability heuristic was used primarily because a new chart was made available to the students which suggested a specific causal factor to pursue. If the student used this causal factor in an appropriate manner and explained it, they were not assigned an availability code. The frequent use of these particular heuristics was an indication that when faced with an unfamiliar situation, students were more likely to use commonsense associations that provided a quick response rather than to work through the more rigorous reasoning that required a thorough investigation and application of multiple domain specific factors.

Consistency of Reasoning from Familiar to Unfamiliar Trends. The introduction of an unfamiliar trend opened the door to some new reasoning strategies for

students. However, the use of these unique strategies did not necessarily mean that more established patterns of reasoning were completely discarded. This section will explore the degree of reasoning consistency that students demonstrated when they moved from familiar to unfamiliar problems as well as the differences that emerged.

Similarities in Reasoning. In order to determine the degree to which students maintained similar reasoning patterns, the reasoning strategies used for the reactivity trend for each student were compared to the two most frequently used reasoning strategies for all of the familiar trends for that same student. Table 4.9 illustrates consistency in student reasoning by showing any reasoning strategy that was used for at least one of the reactivity trends that was also one of the two most frequently used strategies for the more familiar trends.

Table 4.9

Reasoning Strategies that Were Utilized for Both Familiar and Unfamiliar Trends

Student	Reasoning strategies
Corban	Satisficing, Teleological
Karla	Multi-factor
Katie	Multi-factor
Krissy	Multi-factor failure
Loni	Multi-factor
Rhonda	Satisficing, similarity
Sandy	Similarity

An example of a student showing consistency in her reasoning strategies for both familiar and unfamiliar trends, can be seen by comparing a portion of Katie's response for the IE in a group, and her response for the reactivity in a group:

As it goes in a group, I would say the ionization energy will lessen
because there are more shielding orbitals so the pull between a proton

and the valence electron will be less the farther down you go down the column, so then it will take less energy to take that one electron away.

(IE in a group)

I think it has to do with shielding orbitals again because potassium has more orbital energy levels, so the pull or the attraction between the nucleus protons and the valence electrons are going to be less than compared to the lithium protons and the lithium valence electrons so the potassium will be more likely to lose the valence electrons and to give it away because the pull between the protons and electrons is less.

So then it will react more with the water. (Reactivity in a group)

In both of these responses, Katie uses the factors concerning shielding, increased orbitals, and the effect on the nucleus proton attraction for valence electrons. She clearly makes the connection of reactivity to IE and uses almost identical reasoning to explain both trends.

Seven of the thirteen students interviewed continued to make use of a previously used reasoning strategy in conjunction with other strategies when trying to explain an unfamiliar trend. The students showing this consistency included students with both adequate and inadequate DSK.

In addition to consistency in individual reasoning strategies, some students that had been coded as using fixation reasoning with particular factors continued to show the same fixation for at least one of the reactivity trends as shown in Table 4.10. Of the seven students classified as showing fixation reasoning with a particular factor or factor

combination, five continued to use the fixation factors for at least one of the reactivity trends.

Table 4.10

Students Continuing to Utilize Fixation Factors for Reactivity Trend

Student	Fixation Factor(s)
Corban	Number of electrons/full shells
Macy	Number of electrons
Monica	Orbitals/distance
Rhonda	Number of electrons/shells
Ronald	Proton attraction

There were a few additional, but less obvious demonstrations of consistency within student reasoning of familiar and unfamiliar trends. Sonya was classified as having adequate DSK in the domain of ionization, but it still presented her with some challenges. She gave an incorrect prediction for the IE trend in a period and explained it as follows:

The ionization is greater towards the left because the more electrons you lose to the left, it's getting closer to the nucleus and it can eventually jump up to another energy level. So like potassium, if you lost an electron, it will jump up into a different energy level and would go by argon which would require a lot of energy for it to jump up in different levels.

It is unclear exactly what Sonya understood when she described the process of jumping up energy levels, but whatever she is describing seems to require more energy when in an energy level that is closer to the nucleus. She comes back to this same idea when explaining the reactivity in a period when she stated:

Right away, the first ionization energy for potassium had to jump up a level right away, which caused a huge increase right away whereas calcium the first time it lost an electron it wasn't as great of energy, same with iron. But then it took them more energy in the third ionization energy when they lost the third electron. . . . And for iron, it didn't really take that much energy because it never had to jump a different energy level. . . . It doesn't has as much energy going into it.

While it is tempting to notice only the availability reasoning as Sonya used the IE chart showing the various jumps in energy that occur for successive ionizations, when her response is compared to the earlier IE trend reasoning, it is clear that she was drawing on conceptions that had been previously verbalized. She saw the connection of reactivity to IE, and used similar reasoning in her explanation.

Sandy was also consistent in her response to the reactivity trends in a less obvious manner. She relied primarily on her memorization of the trends as discussed earlier and had not given any reason for three previous trends. When asked to explain reactivity, a trend that she had not memorized, she threw out a few ideas in a questioning manner such as charge or mass, then laughed and said, "This is literally torture." Her memorization strategy left her with few resources when given an unfamiliar problem.

Differences in Reasoning. It has already been demonstrated that when students attempted to explain the unfamiliar reactivity trends, they relied more extensively on the common sense strategies of essentialism, similarity and availability. There was an increase in the use of these strategies for both students with adequate and inadequate

DSK. Two students with adequate DSK, Karla and Katie, used a common sense strategy as a starting point and then progressed to more scientific reasoning related to forces.

However, in general there appeared to be a decline in the use of explanations related to forces in student responses to the unfamiliar trend even when the student had used forces in previous explanations as seen in Table 4.11.

Table 4.11

Students who Showed a Decrease in the Use of Forces for Reactivity Trend

Student	Normal type of force reasoning	Excerpt of Reasoning used for reactivity trend
Corban	An increase in electrons cause increased repulsion.	<p>Period: I guess iron has more valence electrons. It's going to want to react less vigorously because it's not going to give up its electrons as quickly as, well as much as potassium or calcium do.</p> <p>Group: Per group if you have more electrons, but you still have one valence electron, it's going to be more vigorous.</p>
Krissy	More electrons cause increased attraction and repulsion. Effect of distance on attraction.	<p>Period: So, size would get larger. I don't know it that makes it more reactive. It would be harder in their reaction to pull away an electron because it would want to move away.</p> <p>Group: I'm guessing it has something to do with size and the bigger it is, the more reactive it is, but I don't know why that would be.</p>
Macy	More electrons cause increased attraction.	<p>Period: I'm guessing it has to do with what kind of element it is, what kind of element it is, what kind of characteristics it has.</p> <p>Group: More electrons then they're more negative. . . . Because the more negative of something, the more it's going to react.</p>
Sandy	More electrons cause increased repulsion. Paired electrons have less repulsion.	<p>Period: It [potassium] reacts more because it is closer to the noble gases.</p> <p>Group: I totally think it has something to do with the charge. . . . The mass is bigger, so it reacts more?</p>
Sonya	Protons cause attraction. Electrons cause repulsion.	<p>Period: It does have to do with the ionization energy of jumping up levels.</p>

In these cases, the use of common sense reasoning heuristics was not a starting point from which more productive reasoning followed, but instead appeared to be a replacement for reasoning that involved forces. Even though many of these students had conceptions about forces that were not scientifically appropriate, they knew that atomic properties were caused by forces. However, when an unfamiliar trend was introduced, they often seemed to forget that forces were involved. In Krissy's explanation of reactivity as seen in Table 4.11, she was sure that size was the cause of reactivity and knew that electrons were being removed, but expressed confusion about the connection. Earlier, when explaining the ionization energy in a group, she was easily able to discuss the forces involved when she stated:

Because there's further energy levels, and the farther it is out from the nucleus where the protons are that's pulling it in, the further the distance, the less the pull or the force.

Krissy was classified as having adequate DSK and had in previous trends used her conceptions of force to facilitate the formation of explanations. She had however, frequently experienced difficulty when working with multiple factors and her focus on electrons as being both the source of attraction as well as repulsion tended to add to her confusion. It is possible that these pre-existing sources of confusion were further exacerbated when she was presented with an unfamiliar situation, which added to the cognitive processing necessary. She became unable to process some of the same ideas that she had used earlier and her explanation necessarily became simplified.

Energy Related Difficulties with Reactivity Trend. When attempting to explain the reactivity trend, not only did students experience difficulty due to the unfamiliarity of the problem, but the problem also highlighted the confusion that five students (Krissy, Rhonda, Ronald, Sonya, and Tina) had concerning the role that energy plays during the course of a chemical reaction. The confusion regarding energy only became evident when the students were given the opportunity to grapple with a problem that was outside of their previous experience and highlights the importance of DSK on student's ability to explain chemical phenomena. This confusion was demonstrated by three answers to a single hypothetical question: What is the origin of the energy that is sometimes produced in a chemical reaction? While the students were never asked this question, they did answer it in part as they attempted to explain the reactivity trends.

The first answer, given by Krissy, was that the energy is supplied by the energy level of the valence electrons and creates the heat released in the reaction. Krissy explained the increased reactivity of potassium as compared to the elements higher in the group by stating:

I know that heat is energy or has to do with energy. So, if we're going down, you're increasing an energy level, which means that if there's more energy, there's more heat. So, it reacts to create more heat if there's more energy to react with.

If Krissy had been asked about the source of energy in a chemical reaction, she might not have answered the question in quite this way, but her answer shows that she really did not have a clear understanding of where the energy comes from. Her answer was logical

using similarity or commonsense reasoning and had the advantage of sounding scientific by referencing energy levels and the idea that heat is a form of energy.

The second answer to the question concerning the source of energy produced in a chemical reaction, is that it is the same energy that is required to get the reaction started. Three students, Rhonda, Ronald, and Sonya, felt that the energy required for a chemical reaction was identical to the energy produced. This conception was born out of the large change in the IE for potassium as you go from the first IE to the second. The difference in these two energies was seen as the amount of energy that was required for the reaction to occur. Sonya expressed this idea by stating:

I would say that it took a lot of energy for this reaction to happen,
which in turn caused the water to become really hot as a lot of work
was being done.

Ronald expressed the same idea saying:

There's more heat involved so it becomes hot enough to burn, so I was
just thinking that intensity [of the reaction] probably comes a lot from
how much energy is actually required to pull away that first electron.

Neither student grasped the idea that if more energy is required, probably the reaction will be slower and less vigorous. Once again, a form of similarity thinking was used because the student did not have a clear conception of the role of energy in the reaction process.

The last answer to the question concerning the source of the energy produced in a chemical reaction was supplied by Tina when she stated:

It would just take something much stronger to react with the iron versus the potassium because it doesn't need as much energy. Maybe the water just didn't create enough energy with it to actually cause a reaction.

Tina appeared to think that the strength of the reacting chemical was the source of the energy needed. This is a very vague conception that is of limited usefulness for future predictions since the definition of "strong" was not provided.

None of the students set out to answer the question concerning the source of energy in a chemical reaction, however the context of an unfamiliar problem helped them to explore this idea. Although only five of the thirteen students verbalized inappropriate conceptions regarding energy, it is possible that other students also harbored some confusion about energy that was not expressed in the course of the interview.

Concluding Statements Concerning Student's Responses to an Unfamiliar Problem. In this section student reasoning with regard to an unfamiliar trend was explored. Three aspects concerning student's response to an unfamiliar problem were investigated: Which heuristics were used primarily for the unfamiliar trend? What were the connections between student reasoning used for familiar trends and the reasoning they used in explaining the unfamiliar trend? Did the unfamiliarity of the reactivity trend highlight any specific conceptual difficulties experienced by the students?

The analysis of student heuristics uncovered four that were used primarily for the reactivity trend. These included the representativeness, essentialism, similarity, and availability heuristics. The representativeness heuristic seemed to be essential if the

student was to connect the familiar trends of ionization energy and radius to the unfamiliar trend of reactivity. Once this connection was made, it did not ensure a scientifically appropriate explanation however. There appeared to be a relationship between the student's ability to give a scientifically appropriate explanation and their DSK. The three other heuristics that were used primarily for explaining the reactivity trend (essentialism, similarity, and availability) were all based on commonsense associations that simplified the problem by enabling the student to consider a single factor without sifting through the effects of multiple causes or giving an in-depth justification.

When comparing the reasoning used by students to explain the familiar and unfamiliar trends, a large degree of consistency was found both in the heuristics used (particularly for satisficing and multi-factor) and for those students who had demonstrated a fixation with particular factors. Seven of the thirteen students continued to use heuristics that they had previously used in conjunction with some of the newer ones mentioned above. The primary difference in student reasoning was that students showed a greater tendency to avoid arguments involving forces. This was reflected by the increased utilization of the commonsense heuristics.

The last aspect investigated regarding student reasoning for the trend of reactivity was that the unfamiliarity of the problem seemed to highlight the conceptual confusion that some students had regarding the source of the energy produced in chemical reactions. Ideas for the source of this energy included the energy level that the electrons resided in,

that it was equivalent to the energy required for the reaction, or that it was created by the presence of another ‘strong’ reactant.

Conclusion

This chapter has reviewed the frequency with which students used specific reasoning strategies in their explanations of periodic trends. Of the four most frequently used strategies, two were of the reduction type that reduced the number of factors considered, usually to a single factor. The heuristic used with the second highest frequency was based on the teleological rule that an atom wants a full outer shell, having an electron configuration similar to the noble gases. The third most frequently used reasoning strategy was the multi-factor strategy which required the student to integrate the effects of more than one factor. This type of reasoning required the most cognitive processing and utilized causal/mechanical reasoning with forces.

Next the relationship between DSK and reasoning strategies was investigated. An adequate understanding of forces was found to have a major impact on student reasoning concerning periodic trends. If a student did not have an adequate understanding of forces, they were more likely to rely on reduction strategies and to demonstrate a fixation with a particular factor in explaining each trend. Those students with an adequate understanding of forces more frequently used multi-factor strategies.

Finally, the reasoning strategies utilized by students when considering an unfamiliar problem were addressed. While many students demonstrated some measure of consistency with previous patterns of reasoning, overall there was an increase in the use

of commonsense strategies and a decrease in the use of causal/mechanical reasoning based on forces.

In the next chapter, a discussion of these findings is presented along with a comparison of the findings of the present study to previous results from the literature. Finally, the implications of these findings for teaching chemistry and ideas for future study, will be discussed.

CHAPTER 5: DISCUSSION

The goal for this study was to gain insight about the difficulties that students experience as they attempt to apply and explain the information contained within the periodic table. The importance of the periodic table to chemists can hardly be overstated. As Scerri (2007) states,

The periodic table of the elements is one of the most powerful icons in science: a single document that captures the essence of chemistry in an elegant form. . . . There are in fact two big ideas in chemistry. They are chemical periodicity and chemical bonding, and they are deeply interconnected (p. xiii).

In order to reach this goal, the present study focused on the reasoning strategies used by students as they attempted to explain various periodic trends. The study involved explanations of both familiar periodic trends as well as trends that required the students to apply what they had learned to a new context. The questions guiding this research were:

1. *What are the types of reasoning strategies used by undergraduate general chemistry students in their explanations of periodic trends including atomic radii, ionic radii, ionization energy, electronegativity and reactivity?*
2. *How does domain specific knowledge concerning atomic structure, electrostatic forces operating within the atom, and the ionization process shape the reasoning strategies of undergraduate general chemistry students in regard to the above trends?*

3. *What effects will an unfamiliar periodic trend problem have on the reasoning strategies utilized by undergraduate general chemistry students?*

In the following sections I summarize the findings that address each of these questions. Since the questions are interconnected, I also show the relationship of the findings to each other. By integrating the insights gained from each question, I hope to extend our understanding of student reasoning in regard to the periodic table. In addition to the discussion of research results, implications of this research are presented with respect to classroom instruction and areas for future research.

Research Question 1: Reasoning Strategies

The reasoning strategies that were most important for students in the present study are provided in Table 5.1. The four most frequently used strategies were: satisficing, teleological, multi-factor, and one-reason. Of these, both satisficing and one-reason strategies belong to the reduction type of heuristic identified by Talanquer (2006) as a reasoning strategy where the problem solver attempts to simplify the problem by reducing the factors that are considered. The one-reason heuristic, as defined in this study, occurred when the student chose to use the factor having the greatest influence on the periodic trend in question and ignored any other contributing factors. An example would be explaining the increasing atomic radius when going down a group by only discussing the increasing number of shells, since each new shell is larger than the previous one. The satisficing heuristic as defined in this study was similar to the one-reason heuristic in that students limited the number of factors considered, but in this case, they ignored factors that were vital to a complete explanation of the periodic trend.

Table 5.1

Summary of Reasoning Strategies by Periodic Trend

Heuristic Code	Periodic Trend						
	Atomic Radius	Ionic Radius	Ionization Energy	Ionization Energy Exceptions	2nd Ionization Energy	Electro-negativity	Reactivity
Additivity	0	5	0	0	2	0	0
Analytical-partial	0	1	0	1	2	2	4
Availability	2	1	1	0	1	2	9
Essentialism	1	0	1	1	0	0	10
Lexicographic	5	2	6	3	1	3	0
Multi-factor	7	6	6	2	7	4	3
Multi-factor failure	1	1	1	3	0	1	4
No reason	1	0	3	4	0	2	0
One-reason	5	7	3	5	5	3	2
Representativeness	0	0	0	0	0	1	15
Satisficing	6	9	8	6	14	11	3
Similarity	2	1	2	0	2	2	10
Teleological	1	1	5	11	9	7	3
Total	33	35	39	38	43	39	64

An example of an explanation coded as satisficing occurred when Nathan discussed the electronegativity going down a group:

Then I believe the trend would increase as you go down the periodic table because there would be more attractive forces. Yes I believe it would have a greater pull as you're going down because there would be more protons.

While Nathan is correct that a greater number of protons will increase the attractive force that electrons feel, he ignores the increased electron repulsion and the influence of increased distance from larger orbitals.

Most of the students who relied on reduction heuristics used factors such as the number of electrons, protons, energy levels, the amount of attraction or repulsion, or the desire for full shells. All of these factors may be useful in a scientifically appropriate explanation of periodic trends with the exception of full shells, however they needed to be combined and weighted appropriately. This was not the case when reduction heuristics were used. In the present study, roughly a third of the total responses were classified as either one-reason or satisficing. While none of the research on student reasoning concerning periodic trends discusses the use of heuristics, the use of heuristics with other chemical topics are available. McClary and Talanquer (2011) when studying student reasoning regarding acid strength, found that 55% of the students used a reduction tactic to limit the number of factors considered, although they only used it for an average of 14% of the tasks assigned. Studies involving molecular polarity (Furió et al., 2000) had similar results, finding that approximately a fifth of the students only considered the

polarity of individual bonds without any consideration of molecular shape to determine overall polarity of the molecule, thus reducing the factors considered to only one. Evans (2006) contended that people have great difficulty in simultaneously dealing with two different possibilities (factors) and are biased to deal with only one. In the present study, even those students who chose the most relevant reason and who explained it adequately, often did not seem inclined to consider other relevant factors. This is consistent with the ideas of Shah and Oppenheimer (2008), that heuristics are used to reduce the cognitive effort required to solve a problem. By considering only one factor, student effort was effectively reduced.

Teleological reasoning (TR) was the second most frequently used strategy by students in the present study. It was exhibited by students with both adequate and inadequate domain specific knowledge. TR is categorized by Talanquer (2006) as a type of empirical mindset, or assumption that substances have a natural or predetermined state that they try to achieve (Taber & García-Franco, 2010). In this study, TR was exhibited as the idea that atoms wish to have full shells like the noble gas elements. Students seemed to think that the atom's need for a full shell (octet of electrons) was the driving force for any change involving electrons. The frequent use of TR, combined with its almost universal appeal, demonstrated its importance to the students in this study. In some instances, the use of TR was helpful in producing a correct prediction or redirecting the reasoning into a more fruitful direction. In about a quarter of the responses, TR was used along with some appropriate use of forces. In most responses however, TR was a substitute for any type of reasoning involving electrostatic forces.

When teleological reasoning was more important to the student than reasoning which relied on electrostatic forces or energy, it was often overgeneralized and used in problems where it did not apply, resulting in an incorrect prediction for the trend. An example of the overgeneralized use of the full shell argument was shown in the explanations of the second ionization energy for an atom with two valence electrons. Three of the thirteen students incorrectly maintained that the second ionization energy would be lower than the first because the atom wanted to lose the second electron in order to have a full outer shell. Even students with adequate domain specific knowledge (DSK) and who used primarily multi-factor reasoning, used teleological arguments for at least some trends. This is consistent with the findings of Kelemen and Rosset (2009), that teleological reasoning is a fundamental aspect of human thought, and while people may suppress this type of reasoning as they gain more scientific explanations, under conditions where processing demands are high, or processing ability is impaired, teleological explanations are more likely to be used. In a more recent study, Kelemen, Rottman, and Seston (2013) state:

This [the study] suggests that there is a threshold to the conceptual revision of teleological ideas-one that even accomplished physical scientists do not breach. A broad teleological tendency therefore appears to be a robust, resilient, and developmentally enduring feature of the human mind that arises early in life and gets masked rather than replaced, even in those whose scientific expertise and explicit metaphysical commitments seem most likely to counteract it (p. 1081).

While the students in the present study had no time limitations, other than self-imposed ones, which would limit their ability to process information, they also did not share the metaphysical commitment that more experienced scientists have to scientific causal/mechanical reasoning. The students were satisfied with the stability of full shell argument, which sounded scientific, usually resulted in correct predictions, and was far easier to comprehend and use. While this may be satisfactory in the short term, Talanquer (2007) claims teleological explanations often hide the true nature of a process, and limit an understanding of the implications and scope of the concepts being explained.

Given the high frequency of student reasoning strategies that relied on reduction and teleological type heuristics, it was surprising to see that multi-factor reasoning was also one of the top four most frequently used reasoning strategies. This was a more complex form of causal reasoning involving multiple factors relating to the electrostatic force interactions between particles. Kuhn et al. (2008) described the importance of what they labeled multi-variable reasoning:

Most commonly, multiple variables co-exist, many of which may influence a particular outcome of interest. Often, then, once the individual effects of each have been ascertained, the task that confronts a scientist (or engineer) is to take all of the relevant effects into account with the objective of predicting how they will jointly affect an outcome. (p. 436).

These explanations did not reach the level of reasoning required by the weighted additive rule as described by Shah and Oppenheimer (2008), but never-the-less represented a

more sophisticated and appropriate form of scientific reasoning than either reduction or teleological reasoning that were the most frequently used strategies in this study.

Research Question 2: Domain Specific Knowledge

Once the most frequently used reasoning strategies were identified, the study explored whether reasoning strategies were uniformly utilized by all students, or how prerequisite knowledge for periodic trends might influence the distribution of reasoning strategies demonstrated. In order to answer this question, the domain specific knowledge (DSK) of students participating in this study was assessed in the domains of atomic structure, electrostatic forces within the atom, and the ionization process. While some students experienced difficulty in all three areas, students experienced the greatest difficulty with electrostatic forces within the atom, with six out of thirteen students being assessed as having inadequate DSK in this domain. Student inadequacy in the domain of the ionization process seemed to mirror that of electrostatic forces, with only one fewer student assessed as inadequate and all other students being identical. While knowledge concerning both forces and the ionization process influenced students' ability to reason, the domain of electrostatic forces seemed to cause the more fundamental difficulty, as every periodic trend must be explained by referencing forces. Thus, without this base, student reasoning regarding the ionization process as well as every other trend must be severely limited. Only three students were assessed as inadequate in the atomic structure domain and the effect on their periodic trend explanations was small. Due to the very large influence that electrostatic forces had on the reasoning strategies used by students, it will be the focus of this conclusion.

Difficulty with electrostatic forces. The primary difficulty that students experienced in the present study was a lack of understanding of basic Coulombic principles. Student difficulties occurred in three areas: the cause of attractive forces including the central role of the positive nuclear charge in attraction, the cause and relative effect of electron repulsion between core and valence electrons, and the relationship of paired electrons. The students that were classified as having inadequate DSK all experienced one or more of these three problems. The lack of clarity regarding either attraction or repulsion resulted in one-sided explanations by many of the students classified as having inadequate DSK. They used either attraction or repulsion, but not both to explain the periodic trends. Of those using attraction, three students felt that the amount of attraction was controlled by the number of electrons rather than the number of protons and this also resulted in incorrect predictions. One student only referred to repulsion which was identified as increasing with the total number of electrons. Two students avoided using any type of force to explain the trends and substituted some combination of shells and distance as the primary focus of their reasoning. Three students had misconceptions regarding paired electrons, thinking that an unpaired electron somehow attracts an additional electron to fill the orbital. This is an example of the overgeneralized usage of the octet or full shells rule which these students extended to see a special stability in full orbitals.

One of the major areas of research regarding student conceptions of electrostatic forces concerns the conservation of force misconception (Taber, 1998; Tan et al., 2008, 2005; Tan & Taber, 2009) which is coded as the additivity heuristic in the present study.

When using additivity, the students regarded nuclear charge as fixed for an atom since the number of protons does not change. If the number of electrons decreased, then the students deduced that each electron must feel more attraction from the set nuclear charge. While the additivity heuristic was used in the present study, it was not the dominant problem that students experienced. Five students used the additivity heuristic, for a total of seven responses, combining it with more valid ideas concerning forces in order to make correct predictions. Four of the five students using this heuristic were categorized as having adequate DSK about forces. This seemed to indicate that, while conservation of force reasoning is not consistent with a scientific conception of forces, it was a type of intermediate conception that was only held by students that were beginning to gain a scientific view of forces.

Influence of inadequate DSK on Reasoning Strategies. Of the students classified as having inadequate DSK in at least one domain, only one student was classified as having an adequate understanding of forces. This means that most students classified as having inadequate DSK in any domain were not able to take advantage of the full range of explanatory power afforded by electrostatic forces. These students had a much higher frequency in their use of reduction (satisficing and one-reason) strategies along with fixation. A student was classified as using a fixation strategy if they followed a similar reasoning strategy based on one or two related factors in at least seven of the fourteen possible problem situations. Seven of the thirteen total students in this study exhibited fixation reasoning and of these seven students, six were classified as having inadequate DSK in at least one domain and five were classified as having inadequate

DSK in forces. The factors that were most frequently fixated on included the number of shells or number of electrons. By using these two factors, the student was able to avoid a detailed discussion of forces, often making a vague reference to distance in the case of shells, or using electrons to justify either more attraction or more repulsion. All students understood atomic structure well enough to identify these two factors and use them in a manner that had a scientific feel, even if they could not tease out the details that would provide a full justification. These findings echo and extend those found by Wang and Barrow (2013), that students with low content knowledge often do not acknowledge the influence of positive nuclear charge, nor are they able to combine the concepts of attraction and repulsion to express effective nuclear charge. These two difficulties often result in fragmentary explanations. In the present study, it was found that not only could inadequate DSK students not combine the concepts of attraction and repulsion, they were often missing one of the two concepts entirely. This deficit in the students' DSK resulted in their use of a consistent strategy based on those tools which they did have, primarily consisting of the number of shells and/or electrons.

In addition to overreliance on reduction strategies and fixation, students with inadequate DSK used the memorization/no reason strategy with higher frequency than those students classified as having adequate DSK. Five students classified as having inadequate DSK in at least one domain used memorization/no reason for a total of ten responses. There were no students classified as having adequate DSK who did not attempt to provide an explanation for every trend, although Corban (a student assessed as having adequate DSK) did express the important role that memorization played in his

learning. Several students expressed the feeling that memorization was their primary means to learn chemistry and that it had been adequate for their high school chemistry experience. This is consistent with the findings of other studies (Salame et al., 2011; Wang & Barrow, 2013) that detail students' overreliance on memorization and their tendency to equate memorization with understanding. The students in the present study who relied on memorization seemed to see it as an effective method of learning which was perhaps easier to negotiate than to learn the complex reasons that would justify any particular periodic trend. Bunce (2009) asserts that memorization can also be the tactic of choice for students who experience fear or insecurity concerning their ability to succeed in chemistry, but that it does not result in learning.

For those students who demonstrated adequate DSK in forces, the range of possible explanations was much greater than for the students whose understanding of forces was limited. These students were able to use multi-factor reasoning with much higher frequency. To be coded as using multi-factor reasoning, the student had to look at two or more factors, demonstrate how they influenced the trend, and weigh them appropriately to determine an answer. Three of the six students with adequate DSK used multi-factor reasoning as their most frequent reasoning strategy and one additional student had it as a close second. Only one student in this group failed to use multi-factor reasoning for any periodic trend. All of the students classified as having adequate DSK used explanations that involved both attractive and repulsive forces, although they did not always combine them in the same explanation. While only one student was able to clearly articulate the concept of effective nuclear charge, several students with adequate DSK

combined nuclear attraction, electron shielding from core electrons and the effect of distance on forces in a scientifically appropriate manner. They were also able to discern which factors were most influential. Simply having an adequate understanding of forces did not ensure scientifically appropriate reasoning, but when students were comfortable with individual factors concerning electrostatic forces, they were more likely to be able to process several factors and combine them in appropriate ways.

The ability of students with adequate DSK to reason with multiple factors in the present study is similar to Wang's (2007) findings of students with high content knowledge. Rather than discussing student reasoning strategies, the study highlighted students' conceptual frameworks. In describing the high content knowledge students, Wang stated:

The links between/among concepts were correct and coherent while explaining a concept or a phenomenon. These students also justified their explanations with appropriate concepts, rather than merely following rules of thumb (2007, p. 146).

Wang highlights the ability of the student's to not only use concepts correctly, but to link them in a coherent manner much like the students in the present study when they used multi-factor reasoning.

Research Question 3: Unfamiliar Trends

In order to answer the third research question, students were asked to explain the reactivity patterns of several metals, a topic that had not been explicitly taught within the unit on periodic trends. It was found that most students continued to demonstrate the

same reasoning patterns that characterized their previous efforts with more familiar problems, however some important differences were also discovered. The unfamiliar trend also highlighted problems in student reasoning regarding energy.

Consistency of reasoning patterns Of the thirteen students in the study, eleven showed some degree of consistency with previous reasoning strategies as seen in Table 5.2. Of the four students using multi-factor reasoning as one of their two most frequently used reasoning strategies, three used it again for at least one of the reactivity trends (either in a period or in a group). One student, Krissy, considered multiple factors for every trend, yet she was unable to weigh their effects properly in order to frame a decision. She experienced the same difficulty when explaining reactivity. Of the seven students that were classified as using a fixation strategy, five continued to show the same fixation for at least one of the reactivity trends. Three of the six students with adequate DSK were able to consider appropriate factors to explain at least one of the reactivity trends, while three of the students with inadequate DSK made a few guesses and then stated that they really could not explain the trends. The rest of the students with inadequate DSK continued to rely on reduction type heuristics, some of which were consistent with their fixation strategies.

Table 5.2

Consistency of Student Reasoning When Crossing the Familiarity Threshold

Student	Consistent – Codes or Fixation Factors*	Different - Codes
Corban	Satisficing Teleological Number of electrons*	Analytical partial
Karla	Multi-factor	Essentialism
Katie	Multi-factor	Availability
Krissy	Multi-factor failure	Similarity
Loni	Multi-factor One-reason	
Macy	Number of electrons*	Similarity Multi-factor failure
Monica	Orbitals/distance*	Essentialism
Nathan		Availability Analytical partial
Rhonda	Satisficing Similarity Number of electrons*	Essentialism Availability
Ronald	Proton attraction*	Analytical partial Availability
Sandy	Similarity	Essentialism
Sonya		Similarity Essentialism Availability
Tina	No mention of force	Essentialism

Differences in reasoning patterns. The major difference in student reasoning strategies that occurred when considering an unfamiliar periodic trend was the increased use of association (blind application of a simple rule) type heuristics including

availability and similarity, as well as the empirical assumption of essentialism used as a heuristic strategy. Each of these strategies enabled the students to make quick decisions about cause and effect relationships in the absence of any clear insight concerning the problem solution.

Essentialism. Eight students used essentialism reasoning for the first reactivity trend while only three used it for the second reactivity trend. It is possible that it was an instinctual reaction to a problem that was unfamiliar and where the answer seemed elusive. When the student could not quickly come up with an explanation they responded that it must have something to do with what type of metal it was, while they tried to think of an answer that had more substance. Karla, who was most consistent in her use of multi-factor reasoning seemed stressed when trying to come up with a reason for the first reactivity trend and used an essentialism strategy. When responding to the second reactivity question, her mind seemed to clear and she easily came up with an appropriate multi-factor response. Essentialism can be evidenced by an appeal to invisible causal mechanisms when those mechanisms are not known. Studies suggest that essentialism may be a childhood bias that carries over into adulthood across a variety of cultures (Gelman, 2005; Gelman et al., 1994). Students in this study used essentialism as a placeholder when they were unable to come up with a more specific reason for the reactivity trend.

Availability. Availability, one of the association type heuristics, was used by six of the students for a total of nine responses to the reactivity trends. It was used for seven responses for all of the other periodic trends combined. The increase in this heuristic was

not simply because the trend was unfamiliar, but because of the availability of a table of ionization energies. Students that were classified as having inadequate understanding of forces often attempted to use the listed ionization energies either without any explanation, or in an inappropriate manner. An example of using the table inappropriately was demonstrated by Rhonda's explanation of the reactivity trend in a period:

It [potassium] takes a bigger ionization energy from first to second then for calcium or iron. I think that it would make it react more. . . . It's gaining electrons because it is bonding with the oxygen and the hydrogen.

She used the table inappropriately by focusing on the difference in energy between the first and second ionization energy rather than comparing the first ionization energy for each element. In this example, Rhonda associates a large gap in the ionization energy with a more vigorous reaction. She demonstrated a lack of understanding of the term ionization energy when she claimed that potassium was gaining an electron rather than losing one.

Similarity. Similarity, also an association type heuristic, was used in ten of the reactivity responses out of nineteen total similarity responses for all trends. The similarity heuristic was used when a student assumed that the cause and effect of a process shared a similar characteristic such as being large. This provided the student with an unjustified association between an obvious structural feature in the atom (number of electrons or energy levels) and the reactivity of the element. An example of using similarity was shown by Macy when she said:

I know it [potassium] has more electrons, but I know they all have the same characteristics because they're [in the] same group. More electrons then, they're more negative. . . . The more negative of something, the more it's going to react.

Macy was unsure of the reason for increased reactivity, so she looked for a similar feature between the atomic structure and the increased reactivity as a way to solve the problem.

Decrease in electrostatic force based explanations. The increase in association and empirical type heuristics was accompanied by a corresponding decrease in the frequency of electrostatic force based explanations. Six students, four with adequate and two with inadequate DSK in electrostatic forces, abandoned their normal force-based explanation for an association, or empirical (essentialism) type heuristic for one or both reactivity problems. This was illustrated by Macy, whose explanation for the reactivity in a group was quoted above. When explaining eight previous trends she had used the argument that more electrons caused increased attraction. She abandoned this reasoning for both reactivity trends and used the essentialism and similarity heuristics. Two additional students, one of which was Karla (the only student who used effective nuclear charge for previous trends) replaced normal force-based arguments for an essentialism or association argument for at least one of the trends. While it is not possible to determine exactly why this occurred, it is clear that the lack of familiarity of the problem caused a shift away from more scientifically appropriate reasoning and towards an inappropriate use of heuristics. It is possible that the increased stress produced by an unfamiliar problem was the cause of the increased heuristic use. Students that were already less than

confident concerning their conceptions of force abandoned these ideas under increased stress in favor of ideas and associations that were easier to access. This idea is reinforced by McClary and Talanquer (2011) who also found that students ranking acid strength relied more heavily on heuristic reasoning in order to make decisions when they were limited in either knowledge or time. Students used the heuristics to, “fill in their knowledge gaps and to compensate for their lack of understanding” (p. 1450). Additionally they found that the students relied more heavily on structural factors rather than electrostatic ones much like students in the present study overused the concept of orbitals rather than thinking through the complexities of balancing attractive and repulsive forces.

Conceptions about energy. In the context of attempting to explain reactivity trends, a number of students also revealed misconceptions regarding the source and role of energy in a chemical reaction. Several students felt that the energy required by a chemical reaction was the same energy that was released as heat when the substance was very reactive; a finding consistent with previous studies (Boo, 1998; Teichert & Stacy, 2002). There was also confusion regarding the relationship between the energy released during a chemical reaction and the energy level of the electrons, the work being done, and the role of the other reactant. It became clear that consistent with other studies, (Becker & Cooper, 2014; Boo, 1998; Taber, 2003b; Teichert & Stacy, 2002) the entire idea of energy as it relates to chemical reactions was a fuzzy concept for the students in this study and sometimes their conceptions seemed to change depending on the context.

Summary, Implications, and Suggestions for Further Research

The present study explored reasoning strategies used by students when asked to scientifically justify various periodic trends. Science is built upon the foundation of cause and effect. What constitutes a scientific justification or cause can be different depending on the specific domain and often involves simplifications of some kind. Which simplifications are appropriate depends on both the problem and the context (Ball, 2018). Harré (2016) explores the meaning of chemical explanations stating:

In chemistry it seems that observations of regularities among phenomena do not end a causal quest but provide the occasion for undertaking a search for hidden causal mechanisms. However, research programs do not end there, but continue in the efforts to identify the *powerful particulars* [emphasis added] that are the source of the capacities to bring about change and to maintain the stability of chemical structures against tendencies to disintegration and decay (p. 197).

Harré then argues that for most of the phenomena that are encountered in traditional chemistry, the *powerful particulars*, *sources of activity*, or *uncaused causes* consist of electrical charges. If this is true, then electrical charges and the resulting electrostatic forces should play an important role in the chemical reasoning used by students to explain the periodic trends. The present study underscored the crucial role that an understanding of electrostatic forces played in determining the ability of students to successfully explain these trends. Those students with an adequate DSK in forces were

more likely to combine and properly weigh the factors dealing with electrostatic forces using multi-factor reasoning. Those students that did not have an adequate DSK in forces were more likely to use reduction and association type heuristics that simplified the explanation to one, often inappropriate, factor. The problems that students with inadequate DSK in forces experienced when they attempted to use electrostatic forces in their explanations affected almost every trend. Many of the students with inadequate DSK were limited in their conceptions to only attractive or repulsive forces and could not combine the two ideas. The conceptions that they did hold were often incomplete or lacking the appropriate focus. Rather than focusing on the role of nuclear charge when discussing attractive forces, the focus was often diverted to the number of electrons or the need for full orbitals or shells. The issue surrounding force-based explanations was exacerbated when the familiarity of the problem context was removed. When presented with an unfamiliar problem, the frequency of reduction and association strategies increased and the reliance on force related factors decreased.

Implications. The most important implication of the present study is that instructors should recognize the difficulties that many students experience in the domain of electrostatic forces and the resulting limitations these students experience as they attempt to understand and explain the periodic trends. Students need more explicit instruction about this topic. Without a thorough understanding of electrostatic forces students cannot be expected to use scientific reasoning strategies about periodic trends which necessarily entail the ability to describe the effect of these forces. Instruction concerning electrostatic forces should focus on the basics of what causes attraction and

repulsion within the atom. Effective instruction should commence well before the unit on periodic trends and should be repeated often to reinforce the concepts (Becker & Cooper, 2014). Prior to any instruction on periodic trends, it would also be beneficial to assess prerequisite concepts with an emphasis on electrostatic forces. Following this assessment, support and scaffolding should be provided to aid students in making connections between electrostatic forces and the periodic trends that are the result of those forces. The instruction should emphasize the primary role of nuclear charge in the attraction of electrons, the difference between the repulsion from valence and core electrons, and how to balance the opposing effects of both types of forces using the concept of effective nuclear charge (Wang & Barrow, 2013). The effect of distance on force must also be demonstrated, and this can be done utilizing Coulomb's Law to show the inverse squared relationship between force and distance (Taber, 1998).

Another implication arising from this study is that instructors need to be deliberate in their instruction concerning heuristics and the mechanics of scientific explanations and they should provide opportunities for students to practice these skills in a variety of venues. In the present study, it was primarily those students with adequate DSK that who were able to utilize multi-factor reasoning. Even these students however experienced difficulty at times when various factors seemed to give opposite results. Twelve out of thirteen students used teleological reasoning, often inappropriately, or without further justification, and all students at some point used heuristics that did not provide satisfactory explanations. It seems clear that the idea of what constitutes an acceptable scientific explanation in the context of chemistry would be a profitable area

for instruction. Students might be taught how to determine the relevance of the various factors that surround a problem. They could be given opportunities to construct or evaluate explanations that involve multiple factors. Since teleological reasoning concerning full shells, or the favorability of the noble gas configuration, seems unavoidable due to its presence in virtually all chemistry textbooks, students should be taught how to effectively use teleological reasoning and other heuristics in a controlled and appropriate manner.

Finally, if we are interested in helping students to grow in their reasoning skills, it might be helpful to encourage metacognitive thinking about their own problem solving and reasoning practices. Giving students opportunities to reflect on when the full shells thinking is productive and why it is productive in those circumstances might help them to see its limitations more clearly. Instructors can encourage students to reflect on their own personal approach to reasoning and problem solving and how their approach might be improved or expanded upon.

Further research. Based on the findings of this study, I suggest the following directions for future research in the area of student chemical reasoning:

- Because the biggest surprise in the present study was the depth of misunderstanding concerning the basics of electrostatic forces, it would be profitable to do a more exhaustive study that explored student explanations concerning the cause of attractive and repulsive forces and how they balance each other within an atom.

- Many of the students in the present study showing a high degree of consistency in the reasoning strategies used in explaining periodic trends. To extend this further, a similar study could be conducted that looked at student reasoning strategies covering several topics, such as periodic trends, molecular bonding, and intermolecular forces to see if any common threads emerge.
- This study found that students with inadequate DSK often had difficulty integrating multiple factors resulting in the increased use of reduction reasoning strategies. In introductory classes, concepts are often simplified to put them within reach of inexperienced learners. As learners become more experienced, it is hoped that they will learn to look at multiple factors in order to construct more robust explanations. Further research should be done to see what might promote a more scientific approach to constructing explanations, specifically in the general chemistry undergraduate curriculum.

Concluding Remarks

The present study looked at student reasoning in the area of periodic trends. It was shown that for the students in this study, the type of reasoning was dependent on domain specific knowledge, and the domain that had the greatest influence was electrostatic forces. Those students with adequate understanding in the domain of electrostatic forces had more resources with which to construct multi-factor explanations, and were able to integrate the factors effectively. Those students without adequate DSK tended to use reduction and association type strategies more often, with the most frequently used strategy being satisficing. They also tended to exhibit fixation by focusing on the same

factor without regard to changes in the problem context. When an unfamiliar problem was presented, the frequency of association and reduction strategies increased, while the incidence of force-related explanations decreased. Even with unfamiliar problems, many students continued to exhibit a consistent reasoning pattern that extended to at least one of the two unfamiliar trends. These findings are significant because of the central role that the periodic table has on the entire discipline of chemistry.

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Appendices

The appendices will include all material that was used in the pilot study, as well as supplementary material that was used within the present study. This includes the tables and figures used to aid the student during the interview, as well as selected questions from the unit exam that helped in the determination of adequate/inadequate DSK.

Appendix A: Interview Protocol for Pilot Study

Periodic Trends Interview Questions

Atomic Representations

1. Write out the electron configuration for a sodium atom.
2. Write out in words what your configuration means.
3. What are orbitals?
4. Draw a representation of a sodium atom showing the charge and position of any particle that you draw. Make sure that you either label each particle or devise some type of key.
5. Relate your picture to your electron configuration.
6. How might a real atom differ from the model you have drawn?

Electrons

7. What does it mean for an electron to be in an orbital?
8. What is the nature of an electron?
9. What is its charge?
10. Identify the highest energy electrons from your drawing.

Periodic Trends

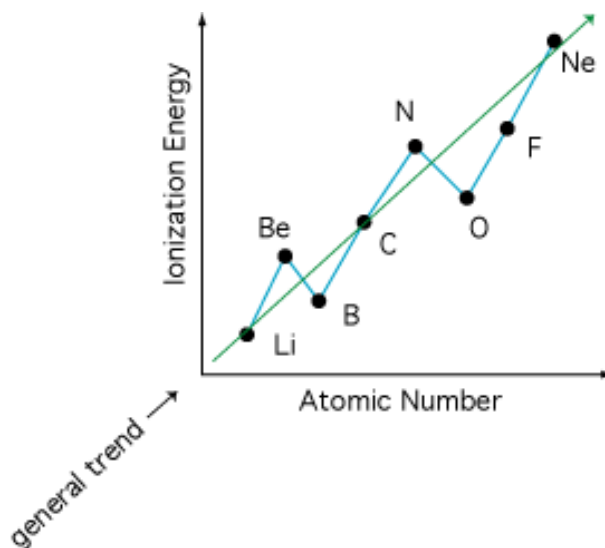
11. Which would be larger in size, a sodium atom or a potassium atom? Explain your reasoning.
12. Which would be larger in size, a sodium atom or a magnesium atom? Explain your reasoning.
13. Draw a representation of a sodium +1 ion using your drawing as a reference.
14. Will a sodium +1 ion be larger or smaller than a sodium atom? Explain your answer being very specific.

15. A fluorine atom can easily become a fluorine -1 ion. Will it become larger or small in size? Explain your answer.
16. Will it require more or less energy to remove a second e^- for sodium ion? Explain.
17. Compare the first ionization energies of sodium, magnesium and aluminum.

Appendix B: Figures and Tables used by Students during Interview

Graph of Trend in First Ionization Energy for Period Two (Grandinetti, 1995)

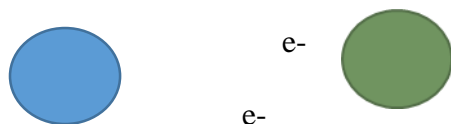
(Used with interview question 7)



Electronegativity Figure

(Used with interview question 9)

Electronegativity – the tendency of an atom to attract electrons in a bond.



Explanation: The green atom is more electronegative because the shared electrons are closer to it than the blue atom.

Reactivity Figures and Charts

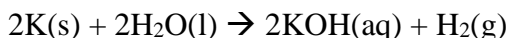
(Used with interview questions 10-11)

Successive Ionization Energy (IE) of Three Group 4 Metals in kJ/mol (“Molar ionization energies of the elements,” 2016)

Element	1 st IE	2 nd IE	3 rd IE	4 th IE
Potassium	419	3052	4420	5877
Calcium	590	1145	4912	6491
Iron	763	1562	2957	5290
Ionization Energy (IE) of Three Group 1 Metals in kJ/mol				
Lithium	520	7298	11815	
Sodium	496	4562	6910	
Potassium	419	3052	4420	

Reactivity across a period

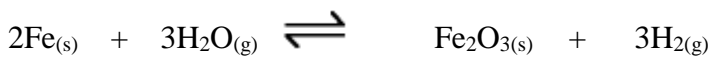
Potassium reacts vigorously with cold water and becomes hot enough to burn.



Calcium reacts slowly in cold water.

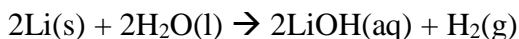


Iron will react poorly with steam.

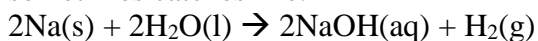


Reactivity down a group

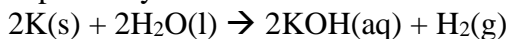
Lithium reacts with water and generates heat.



Sodium reacts even more vigorously to produce more heat, so that the hydrogen gas sometimes catches fire.



Potassium reacts **very** vigorously with water with much heat and the hydrogen burns explosively.



Appendix C: Exam Questions

Questions Used to Assess DSK (Tamarack Software, 2009)

1. There are _____ orbitals in the third shell.
- 4
 - 16
 - 9
 - 1
 - 25
2. Which one of the following is the correct electron configuration for a ground-state nitrogen atom
- a.
- | 1s | 2s | 2p |
|----|----|-------|
| ↑↓ | ↑↓ | ↑ ↑ ↑ |
- b.
- | 1s | 2s | 2p |
|----|----|------|
| ↑↓ | ↑↓ | ↑↓ ↑ |
- c.
- | 1s | 2s | 2p |
|----|----|-------|
| ↑↓ | ↑↑ | ↑ ↑ ↑ |
- d.
- | 1s | 2s | 2p |
|----|----|-------|
| ↑↑ | ↑↓ | ↑ ↑ ↑ |
- e. None of the above is correct.
3. Screening of the nuclear charge by core electrons in atoms is _____.
- less efficient than that by valence electrons
 - essentially identical to that by valence electrons
 - responsible for a general decrease in atomic radius going down a group
 - more efficient than that by valence electrons
 - both essentially identical to that by valence electrons and responsible for a general decrease in atomic radius going down a group

4. Which of the following will require a huge increase in energy when going from the second ionization energy to the third?
 - a. Ge
 - b. Ca
 - c. Se
 - d. K
 - e. Ga
5. The complete ground state electron configuration of Ga is:
6. The condensed electron configuration of scandium is _____.
7. What is meant by the first ionization energy?

Appendix D: Atomic Structure Student Assessment Used in Pilot Study

The following questions were used in the pilot study as a class assignment. (The actual assignment provided appropriate space for pictures and full explanations.)

Periodic Properties Assessment

1. Write out the electron configuration for a sodium atom.
2. Write out in words what your configuration means from question 1.
3. Draw a representation of a sodium atom showing the charge and position of any particle that you draw. Make sure that you either label each particle or devise some type of key.
4. Identify the highest energy electrons from your drawing.
5. Which would be larger in size, a sodium atom or a potassium atom? Explain your reasoning.
6. Which would be larger in size, a sodium atom or a magnesium atom? Explain your reasoning.
7. Draw a representation of a sodium +1 ion using your drawing in #3 as a reference.
8. Will a sodium +1 ion be larger or smaller than a sodium atom? Explain your answer being very specific.
9. A fluorine atom can easily become a fluorine -1 ion. Will it become larger or small in size? Explain your answer.